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13. ABSTRACT *(Maximum 200 Words)*

[1]The MCIM was founded four years ago with the objectives of broadening the education of students by providing them research opportunities in industry. The MCIM faculty visit industry to identify projects at the Master's and Ph.D. levels. Part of the support from the AFOSR provided time-release for the MCIM faculty to make the necessary contacts with industry and to develop an education and research program in the mathematics department: new courses in applied and computation mathematics and co-mentoring students (together with industrial people). Another part of the support was to students who worked with industry.

Due to the successful record of the students, by now most industries support the students during their internship period. They also support Ph.D. students whose research is based on projects from industry. The students that sought to get only Master's degrees found good positions in industry, where they successfully apply their mathematical training.

[2], [3], [4] - Please see the respective sections within body of report for summaries.

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Final Report for AFOSR

New Priorities for a Changing U.S. Economy

Grant Number: AFOSR/F49620-94-1-0461

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Minnesota Center for Industrial Mathematics
Final Report for AFOSR

OBJECTIVES

The objective of the Minnesota Center for Industrial Mathematics (MCIM) was to demonstrate to industry the value of mathematics in research while at the same time preparing students for job opportunities in industry and government. This has been accomplished through student internships at industrial sites. The internship, which lasts 3 months, is co-mentored by an industry researcher and a faculty member at the MCIM. As an indication of the success of the program, the majority of funding for the interns was provided by industry; industry also provided free time for its researchers to mentor the students.

STATUS OF EFFORT

Below is a list of students' who successfully completed internships in industry. Financial support was provided by the grant as well as from financial contributions from companies participating in the MCIM's industrial mathematics internship program. These students are pursuing Master's or Ph.D. degrees in Industrial and Applied Mathematics. The students' theses were based on research conducted while completing the internship.

1. Yi-Ju Chao, Ph.D. Candidate
   Internship: Motorola
   Research Project: Queuing theory for cell phone patients.
   Dissertation Research: Queuing Theory
   Academic Advisor: Professor Nikolai Krylov

2. Michael Lee, Master's Graduate Student
   Internship: Medtronic
   Research Project: Comparison of numerical methods for structural analysis

3. Irina Mitrea, Master's Graduate Student
   Internship: 3M
   Research Project: Model of electrodeposition

4. Martin O'Hely, Ph.D. Graduate Student
   Internship: Lockheed Martin
   Research Project: Data fusion

5. Gerardo Ortigoza, Master's Graduate Student
   Internship: Honeywell
   Research: Research in fiber optics

6. Svetlana Rudnaya, Ph.D. Candidate
   Internship: Ford Motor Company
   Research Project: Analysis of air pollution
   Dissertation Title and Research: "Optimization algorithm for designs of optical phase masks". Ms. Rudnaya is currently working on a problem in optical phase mask design for her dissertation. She is expected to graduate in June 1999.
   Academic Advisor: Professor Fadil Santosa

7. Scott Shald, Ph.D. Candidate
   Internship: Honeywell
   Dissertation Title and Research: "Problems in Estimation." His research involves the detection and tracking of targets. He will complete his Ph.D. in December 1998.
   Academic Advisor: Professor Avner Friedman.

8. Luis Yunes, Master's Graduate Student
   Internship: Banner Engineering
   Research Project: Development of a vision system

9. Aleksandar Zatezalo, Ph.D. Graduate
   Internship: Lockheed-Martin Tactical Defense Systems
   Dissertation Title and Research: "Filtering of Partially Observable Stochastic Processes." Mr. Zatelazo, who completed his Ph.D. in June 1998, focused on developing an algorithm for detection and tracking of targets in a cluttered environment. His research with Lockheed Martin was on detection of multi-targets.
   Academic Advisor: Professor Nikolai Krylov

ACCOMPLISHMENTS/NEW FINDINGS

The research accomplished by the Ph.D. candidates included:

Scott Shald
Ph.D. Expected: 1999
Dissertation Research in "tracking problems".
Mr. Shald developed a scheme, which tracks a target with information of only line of sight.

Aleksandar Zatezalo
Ph.D. Awarded: June 1998
Dissertation Title: "Filtering of Partially Observable Stochastic Processes."
Mr. Zatazalo developed an algorithm, which determines whether, in the presence of noise, there is a target in view.

PERSONNEL SUPPORTED

Faculty partially supported
Avner Friedman, P.I.

Graduate Students supported
Pavel Belik, (Ph.D. expected 1999)
Yi-Ju Chao, (Ph.D. expected 1999)
Michael Lee, (M.S. expected 2000)
Irina Mitrea, (M.S. expected 1999)
Martin O'Hely, (Ph.D. expected 1999)
Gerardo Ortigoza, (M.S. expected 1999)
Svetlana Rudnaya, (Ph.D. expected 1999)
Scott Shald, (Ph.D. expected 1999)
Luis Yunes, (M.S. expected 1999)
Aleksandar Zatezalo, (Ph.D. received 1998)

PUBLICATIONS

1. Shald, Scott (Ph.D. Candidate). "The Continuous Kalman Filter as the Limit of the Discrete Kalman Filter," *Stochastic Analysis and Applications*, accepted.

INTERACTIONS/TRANSITIONS (OUTREACH ACTIVITIES)

During the 1997-98 academic year, Dr. Avner Friedman, Director of the MCIM and Dr. Fadil Santosa, Associate Director of the MCIM, visited many companies including Boeing, Schlumberger-Doll Research, Lucent Technologies, IBM, Kodak, in addition to local companies such as Guidant Computing Devices International, Deluxe Corporation, 3M, Honeywell, Loram Maintenance of Way, Medtronic, and Lockheed-Martin. The visits helped in generating interest in our industrial mathematics graduate studies program and research collaborations.

Participation/presentations at meetings, conferences

1. Aleksandar Zatezalo (Ph.D. graduate), Second International Conference on Non-Linear Problems in Aviation and Aerospace, Orlando, Florida, April 29-May 1, 1998

2. Svetlana Rudnaya (Ph.D. Candidate), Visit to Ford Research Laboratories, Dearborn, Michigan, May 1998

3. Professor Fadil Santosa, Presentation/Workshop, Department of Mathematics, Utah State University, June 3-5, 1998

4. Professor Fadil Santosa, Presentation at the *4th International Conference on Wave Propagation,*Golden, Colorado, June 12-14, 1998

5. Professor Fadil Santosa, Presentation at the *National Institute for Science Education Conference and the Graduate Studies Forum*, Washington, D.C., June 29-30, 1998

6. Professor Fadil Santosa, *Industrial Mathematics Presentations* at Boeing Corporation and University of Washington (Applied Mathematics Department), Seattle, Washington, August 25-28, 1998

7. Professor Fadil Santosa, Presentation at the 2nd Conference *on Minorities and Applied Mathematicians with Connections to Industry and National Laboratories*, University of California-Berkeley, September 17-19, 1998

8. YiJu Chao (Ph.D. Candidate), *Allerton Conference on Communication, Control, and Computing,* University of Illinois at Urbana-Champaign, September 23-25, 1998

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None.

HONORS/AWARDS

1. YiJu Chao received a Master's of Science degree in Mathematics (emphasis in Industrial and Applied Mathematics) in March 1998. The title of her thesis is *Mathematical Approaches to Predictive Health Monitoring for Heart Failure Patients.* Currently, Ms. Chao is pursuing a Ph.D. in Applied Mathematics at the University of Minnesota and expects to graduate June 1999.

2. Jennifer Treadway received a Master's of Science degree in Mathematics (emphasis in Industrial and Applied Mathematics) in June 1998. The title of her thesis is *Computer Assisted 3-D Reconstruction from Images.* Ms. Treadway currently works for Evans and Sutherland, Salt Lake City, Utah.

3. Yan Xin received a Master's of Science degree in Mathematics (emphasis in Industrial and Applied Mathematics) in June 1998. The title of his thesis is *An Analysis of Pacemaker Wire Leads.* Mr. Xin is currently employed with LORAM Maintenance of Way.

4. Aleksandar Zatezalo received a Doctor of Philosophy in Mathematics (emphasis in Industrial Mathematics) in June 1998. The title of his dissertation is *Filtering of Partially Observable Stochastic Processes.* Dr. Zatezalo currently holds a post-doctoral position in the Institute for Mathematics and Its Applications, University of Minnesota.

Freeman Center for International Economic Policy
Final Report to AFOSR

1. Improving Data Use for Economic Adjustment – Lee Munnich

This subproject aimed to establish a major source of quantitative information and techniques to serve state and local policymakers engaged in the process of economic reorientation and development.

The Database for Economic Adjustment work plan included four major tasks or focus areas:

- identification, collection, and analysis of information, data and analytical methods related to industry analysis
- development of a framework for industry analysis
- development and testing of a delivery mechanism
- evaluation of the project

Identification, collection, and analysis of information, data, and analytical methods related to industry analysis. The project team conducted a review of data sources, analytical techniques, and frameworks for analysis that may be of use to communities interested in understanding their industries and developing appropriate related policies and programs. The project team conducted meetings with its technical and faculty advisory committees to further hone the scope of the project, identify and assess various data sources and analytical techniques, and address specific questions about the project's target audience and how to reach it.

The project team conducted a telephone survey of economic development researchers from 35 states to identify data and techniques states and local areas use in analyzing their industries, measure demand for a widely accessible framework for industry analysis that includes access to data, and determine the best way to reach local and state economic development practitioners. In addition to receiving useful information on data and techniques, the project team also learned that local economic development practitioners are in great need of an easy-to-use framework for understanding their industries and easier access to data and that a World Wide Web site would be the best way to reach the largest number of people.

The project team identified and studied three areas that have used industry-based strategies to direct their economic development efforts and would serve as interesting and instructive examples to other states and local areas. The project team developed case studies that highlighted these three areas: Minnesota and two of its regions, Oregon, and Cleveland, Ohio.

During the first year of the project, a subcontractor, the Northeast-Midwest Institute produced a draft design of a labor market information system that would 1) consolidate labor market information functions from many parts of the Department of Labor into the Bureau of Labor Statistics; 2) expand the Bureau's line of products to include state and local data; 3) provide for a larger role for states in labor market information decisionmaking; and 4) streamline the Department of Labor's funding process for labor market information.

After producing the initial draft design, Paula Duggan of the Institute's staff met several times with policymakers to discuss the current operation of the labor market statistical system and how the draft design would address concerns with the system. Institute staff also prepared memos in answer to particular issues, worked to refine the proposed design, and performed comprehensive analysis of current labor market information proposals.

Development of a framework for industry analysis. Based on its research, meetings, and interviews, the project team developed a framework that state and local governments can use to analyze their industries and identify those that are of greatest importance to the area's economy.

Development and testing of a delivery mechanism. After completing the research and consultations described above, the project team decided that a World Wide Web site would be the best delivery mechanism to use since it would reach the greatest number of people, is low-cost, can be updated easily, and could link communities with other useful data and information sources.

An Economic Development website for state and local economic development professionals was completed, tested, and opened to public use. The website address is http://www.hhh.umn.edu/Centers/SLP/edweb. The purpose of the website is to facilitate better use of available on-line data sources and to improve economic development policy making. The website includes (1) explanations of how to apply specific analysis techniques to understand regional and local industries, (2) sample interpretation and policy implications of analytical techniques, (3) employment and data sources on the Internet, (4) evaluation of the relative merits of each data site, (5) the State and Local Policy Program's (SLPP) ten Emerging Principles for Economic Development with 24 case study examples of how to apply these principles, and (6) economic development and data links by state.

The website includes the methodology for conducting industry analysis using shift-share analysis or location quotients, links to data sources to conduct this analysis, and qualitative techniques for understanding industry clusters. The project team conducted a beta test with forty graduate students during a course taught by Professor Ragui Assaad of the Humphrey Institute. The beta test indicated that the website was a useful tool for individuals with moderate quantitative and computer skills and provided an efficient way of accessing the necessary data. The website was introduced at the Humphrey Institute's "Innovations in Economic Development" conference in April 1997 and has also been promoted through list serves and at other conferences attended by economic development professionals. As more state and local governments join the World Wide Web, we expect increasing use of this site.

During the summer of 1997 the web master for the site received feedback from a number of users, all positive or recommending minor improvements. The information included on the website has also been compiled as a hard copy report in the event that a potential user does not have access to the Internet or prefers to work with a printed report. This report, of course, does not include the data links and links to state economic development sites that are available through the Internet.

Evaluation of the project. Interviews with state economic development professionals, meetings with the technical and faculty advisory committees, and consultations with other economic development professionals throughout the process provided useful assessments and ideas for revising and improving the project.

To supplement and expand upon issues directly related to applying the industry based approach to economic development, the State and Local Policy Program sponsored a national conference at the Humphrey Institute of the University of Minnesota on April 11-12 of 1997. This conference was co-sponsored by the Humphrey Institute and the Denver-based Center for the New West. In addition to support from this grant, the conference and proceedings were funded with grants from the U.S. Economic Development Administration, Northern States Power, Advantage Minnesota, and by participant fees. This conference convened 170 policy makers, economic development professionals and business leaders from 24 states to exchange cutting-edge techniques for promoting local and regional economic development in the rapidly evolving, knowledge-based economy.

The conference included a preconference dialogue on the use of economic data for industry analysis and economic adjustment and conference presentations on resources and effective strategies for using economic data for industry analysis and program evaluation. The conference participants were encouraged to review and provide feedback on the Economic Development Website. The proceedings of the conference were transcribed and reviewed by speakers and were professionally edited. The report is available through the website as well as in printed form.

In May 1997, SLPP convened over 40 Minnesota economic development professionals for a roundtable discussion regarding an industry cluster approach to economic development. Economic development policies targeted to clusters of industries can improve program efficiency, promote collaboration, and increase understanding of growth dynamics with regional economies. SLPP pioneered an industry cluster analysis technique through research in the Twin Cities and southeastern Minnesota. The roundtable offered an opportunity for economic development professionals to learn more about this emerging approach and to discuss possible implications for School-to-Work and Welfare-to-Work initiatives.

2. Assembling a Data Base Linking Foreign and Domestic Sectors – John S. Chipman

This subproject attacked the problem of differing data sets produced by the United States government for production and for foreign trade. The work focussed on constructing a data base of U.S. imports and exports, as well as import and export indices, according to a classification system that is consistent with those employed in domestic data such as the producer price index and index of industrial production.

The Bureau of the Census of the Department of Commerce has been making import and export data available in machine-readable form only since 1989. This is in the form of CD-ROMs, one for each month. The CD-ROMs contain the monthly data on values and quantities, although in the case of some categories, which –even at the finest level of classification –contain aggregates (an example is "rabbits and hares"), no quantity data are provided. Even in the case of categories for which this is not a problem, quantity data are available for some shipments but not all – for reasons that remain to be established. Professor Chipman was interested in the quantity data in order to construct a series on "volumes" – a quantity index in which quantities are weighted by unit values in the base year. The quotient of values by volumes then furnishes unit values for the categories. Since the import and export price-index data furnished by the Bureau of Labor Statistics cover only fourth months per year, the aim is to use the monthly unit-value data as a related series in order to interpolate the BLS series into a monthly series. Since the publicly available data are available only since 1989, they could not be profitably used in economic research unless made available on a monthly basis.

The monthly CD-ROMs contain the detailed data to the "Harmonized System" and also the conversion keys from this system to both SIC and SITC (finest categories). To estimate volumes, it was assumed that categories for which quantity data are available are representative of those for which the quantity data are unavailable; thus values and volumes, hence also unit values, will be generated on a monthly basis. These data were also used to generate weights for the BLS price indices, making it possible to obtain monthly price-index data classified by both SIC and SITC.

This work was automated using the latest version of Lahey's Fortran 90 software. A high-capacity Zip drive was also purchased. It enabled archiving of the data as the project proceeded.

Professor Chipman discovered that the CD-ROMs issued by the Bureau of the Census contain a complete concordance table allotting each ten-digit Harmonized System category to the appropriate finest category of the SITC, SIC, and End Use classification systems. The Census Bureau also provided custom made CD-ROMs covering imports and exports data not otherwise available.

It became clear that the Census Bureau data are characterized by many outliers and "structural changes" as described in the paper, "Computation of Approximate Monthly Price and Quantity Series for U.S. Imports and Exports According to Four Classification Systems, January 1990 – March 1996" (with Hwikwon Ham). The structural changes result from an error in the method of producing the data; the outliers result from errors in the reporting of the data by the primary sources and/or in entering the data into the CD-ROMs. This research therefore turned in the direction of developing methodologies for handling outliers and structural changes in these data. The standard statistical literature on robust estimation was very helpful, but does not cover these types of economic time series, and had to be further developed. The other challenging problems resulted from the fact that the BLS price-index data had ceased being issued in terms of the SIC classification, whereas this was the crucial classification system needed to integrate international with domestic data. The more complete SITC data set was used to test various methods of extrapolation using the unit-values series as related series; having found a satisfactory method, the BLS's SIC series was updated. The main approach of the Kravis-Lipsey school of thought has been to disparage and avoid the use of unit-value data because of their unreliability; the approach of this project was instead to recognize that there is some valid information contained in unit-value data, but it must be carefully filtered out.

In the third year of the project, Professor Chipman used detailed 10-digit data to produce a set of monthly data on U.S. import and export prices classified according to SITC, SIC, and other classification systems. As a benchmark, he used the BLS price-index system. For the first part of this period BLS data are available only quarterly. They are available according to the SIC in the early part of the period, but for some reason have been discontinued; recent data have included data classified according to the "Harmonized System" (HS) and the End Use classification (EU). Only the SITC were available for the whole period. Thus, Professor Chipman and his research assistant, Hwikwon Ham, used the SITC data to test their method. The CD-ROMs allowed one to employ any four of the above-mentioned classification systems.

It is well recognized by the most expert and experienced statisticians working in the area of robust data analysis (e.g., Tukey, Huber, etc.) that – at least in the present state of the art – one cannot avoid using subjective graphical methods. The best one can do is to minimize the subjective element. Professor Chipman found in the course of this research that two types of outliers must be sharply distinguished: (1) sudden one-period departures from "normal" followed in the next period by a return to "normal"; and (2) sudden once-for-all changes in level. He interprets the latter as resulting from a change in the methods used to classify commodities when new products are introduced; for example, some new commodities have to be excluded until the classification system (whether HS, SITC, or other) is revised to encompass them. In the latter case, if we take first differences of the (logarithms of the) data, then a structural change appears as an outlier in the first differences. When this outlier is removed and the data are transformed back by summation, the structural change, of course, disappears. This method was very successful in correcting the unit-value data to conform to the price-index data. This phenomenon has not been considered in any of the standard statistical treatments of outliers. One problem with this method, however, is that if it is used when genuine outliers (as opposed to structural changes) are present, it creates a downward bias in the adjusted smoothed data. To correct for this, one needs to use logarithms of the raw data, rather than differences in these logarithms. Thus, the method used must depend to some extent on a subjective evaluation of the nature of the singularity in the data.

Papers resulting from grant funding:

"Computation of Approximative Monthly Price and Quantity Series for U.S. Imports and Exports According to Four Classification Systems, January 1990 – March 1996," preliminary version, 1 September 1996 (with Hwikwon Ham).

"Extracting Reliable Information from Monthly Unit Values: A Problem in Robust Smoothing."

3. General Equilibrium Modeling of U.S. Adjustment and the Global Economy – Timothy J. Kehoe

This subproject refined general equilibrium modeling techniques to explore the impact of changing foreign trade patterns on specific industries and regions.

The research dealt with two overlapping topics:

- analyzing, constructing, and calibrating dynamic general equilibrium models to study policies related to trade and capital flows.
- studying the causes of the 1994-95 financial crisis that started in Mexico and subsequently spilled over into much of the developing world.

In connection with the first topic, Professor Kehoe constructed a calibrated dynamic general equilibrium model of North American trade and capital flows. Preliminary results indicate that large capital inflows, an appreciation of the real exchange rate and a decline in the domestic savings rate are exactly what should be expected when a relatively poor, relatively young, country like Mexico opens to foreign investment.

In connection with the second topic, Professor Kehoe with Caroline Betts of the University of Southern California conducted research on the relationship between fragility in the domestic banking sector and currency crises. Evidence suggested important links not just in Mexico in 1994, but in both developing and developed countries throughout the world over the past twenty years. A dynamic general equilibrium model was constructed to study this relationship. Their empirical work also showed that fluctuations in the U.S.-Mexico real exchange rate has been largely driven by changes in the relative prices of non-traded goods as predicted by this model.

Professor Kehoe also worked with Gonzalo Fernandez de Cordoba of the Universidad de Salamanca to use this model to explain the capital flows and exchange rate movements that followed Spain's integration in the European Community in 1986.

Also in connection with the second topic, Professor Kehoe extended his joint work with Harold Cole of the Federal Reserve Bank of Minneapolis. This work modeled the Mexican government's inability to roll over its short-term debt in late December 1994 and January 1995 as a self-fulfilling crisis: the fears on the part of investors that Mexico would default on its debt created conditions in which a default seemed inevitable. They later investigated the possibility of modeling Mexico's devaluation as another self-fulfilling crisis.

Professor Kehoe was awarded a three year, $178,454 grant from the National Science Foundation ("Modeling International Capital Flows and Real Exchange Rate Movements," SBR-9618370) to continue work on this project.

Papers resulting from grant funding:

"Can Debt Crisis Be Prevented?" in Edward Altman, Richard Levich, and Jianping Mei, editors, The Future of Emerging Market Capital Flows, Richard D. Irwin, 1997.

"Capital Flows and North American Economic Inegration," in Richard E. Baldwin and Joseph Francois, editors, Dynamic Issues in Applied Commercial Policy Analysis, Cambridge University Press, 1997.

Comments on "Are Currency Crises Self-Fulfilling?" by Paul Krugman, in Ben S. Bernanke and Julio J. Rotembert, editors, NBER Macroeconomics Annual 1996, MIT Press.

"A Dynamic Model of Capital Flows and Real Exchange Rates in North America."

"Self-Fulfilling Debt Crises," with Harold L. Cole.

"A Self-Fulfilling Model of Mexico's 1994-95 Debt Crisis," with Harold L. Cole, Journal of International Economics, 1997.

"Social Accounting Matrices and Applied General Equilibrium Models," in Ian Begg and Brian Henry, editors, Applied Economics and Public Policy, Cambridge University Press, 1997.

Presentations at seminars, conferences, or meetings:

"Can Debt Crises Be Prevented?" Conference on the Future of Emerging Market Capital Flows, NYU, May 1996.

"Capital Flows and North American Economic Integration," National Institute for Economic and Social Research, London, December 1995; XX Simposio del Analisis Economico, Barcelona, December 1995; CEPR Conference on Dynamic Trade Policy Analysis, Geneva, January 1996.

Discussion of Paul Krugman, "Are Currency Crises Self-Fulfilling?" NBER Macro Annual Conference, Cambridge, Massachusetts, March 1996.

"A Dynamic Model of Capital Flows and Real Exchange Rates in North America," Society for Economic Dynamics and Control Meetings, Mexico City, July 1996; Workshop on Dynamic Macroeconomics, Universidad de Vigo, July 1996.

"The Financial Crisis in Mexico," Lakehead University, November 1995; El Collegio d'Economistes de Catalunya, April 1996; University of California Riverside, April 1996; Universidad autonoma de Barcelona, May 1996; Fundacion Caixa Galicia, La Coruna, July 1996.

"Self-Fulfilling Debt Crises," University of Southern California, November 1995; Federal Reserve Bank of Minneapolis, December 1995; conference on Speculative Attacks in the Global Economy, University of Maryland, December 1995; North American Economics and Finance Association Meetings, San Francisco, January 1996; Princeton University, February 1996; Instituto Autonomo Tecnologico de Mexico, March 1996; Universidad de Pais Vasco, May 1996.

"A Self-Fulfilling Model of Mexico's 1994-95 Debt Crisis," UCLA, April 1996; University of Southern California, April 1996; Universidad de Alicante, April 1996; Universidad Pompeu Fabra, May 1996; Universidad Carlos III, May 1996; Conference on Growth and Business Cycles, Santiago, Spain, July 1996; NBER Summer Institute, Cambridge, Massachusetts, July 1996; Conference on Policy Rules and Tequila Lessons, Buenos Aires, August 1996.

"Social Accounting Matrices and Applied General Equilibrium Models," Fiftieth Anniversary of the Department of Applied Economics Conference, University of Cambridge, December 1995.

"The Discipline of Applied General Equilibrium" 2eme Colloque Theories de la Macroeconomie, Catholic University of Louvain, May 1997, (Plenary Address).

"A Dynamic Model of Capital Flows and Real Exchange Rates in North America," Latin America and Caribbean Economics Association Meetings, Mexico City, October, 1996, UCLA, January 1997; Universidad Pompeu Fabra, April 1997; Federal Reserve Bank of Atlanta, October 1997; Duke University, November 1997.

"The Financial Crisis in Mexico," Roundtable on Speculative Attacks, Latin American and Caribbean Economics Association Meetings, Bogota, October 1997.

"Self-Fulfilling Debt Crises," XXI Simposio del Analysis Economico, Barcelona, December 1997.

4. Personnel Practices and Economic Adjustment – Morris M. Kleiner

This subproject considered the relationship between employee involvement practices and the productivity of firms in both defense and non-defense sectors.

Professor Kleiner's initial effort focused on gathering data from manufacturing organizations that have had employee involvement programs and ones that did not. Researchers interviewed defense-related establishments and manufacturing plants that have large defense manufacturing and ones that do not deal with defense to examine whether the rate of innovation is greater among defense-related organizations. Over thirty private sector organizations agreed to talk about their employee involvement programs. The interviews focused on the kind of program that the organization has implemented and the success of the program in enhancing productivity.

Given the use of a smaller number of firms, but more detailed information about each firm, a new methodological tool called "Qualitative Comparative Analysis" was used. This approach employs boolean algebra to estimate the logic of the joint usage of alternative personnel policies within an organization. Both qualitative and quantitative information was organized in a format to estimate models based on this approach first developed by Charles Ragin in his prize-winning book, The Comparative Method. Models based on this approach were estimated during the summer of 1996, when the data collection effort was complete.

Based on the research completed in the first year of the grant, Professor Kleiner presented papers at the University of Cambridge, England; INSEE, France; MIT, USA; and the University of Minnesota.

During the second year of the grant, Professor Kleiner and the research assistants funded from this project visited 35 plants that have high, low, and medium levels of employee involvement. They compared defense-related industries to those in the civilian sector regarding their employee involvement programs. In addition, Professor Kleiner and his associates developed a questionnaire that addressed the role of other personnel policies such as compensation policies within the employment relationship. The personnel information was then linked to the LRD, a data system developed by the Census Bureau specifically to examine changes in U.S. manufacturing. They also analyzed a new data set from the Society for Human Resources Management that contained information on employee involvement programs for over 350 publicly traded organizations. This larger data set contains information on both defense and nondefense companies. The personnel policies for each of these organizations was then linked to productivity and profitability information available through COMPUSTAT data on US firms. Papers using these data sets appeared in publications at the National Bureau of Economic Research and at a session at the American Economic Association at its annual meeting in January, 1997.

The major findings were that there were no major differences between defense-related industries relative to nondefense establishments regarding the impact of changes in personnel policies on economic performance. This finding is robust using either case studies over time or the use of cross sectional analysis using publicly-traded companies at a point in time.

In the third year of the grant Professor Kleiner produced three additional papers. In each case funding was used to gather data from individual manufacturing establishments and provide linkages to information on economic performance. For the most part the data from the defense-related manufacturing establishments were gathered by visits to the plants and interviews with the persons in these organizations. The presentations and a brief summary of the main findings are noted below.

A paper entitled "The Anatomy and Effects of Employee Involvement" was presented at the July 1997 meeting of the "Productivity Section" of the National Bureau of Economic Research in Cambridge, Massachusetts. This study used support form the grant to collect data from the Society for Human Resource Management, which included firm profitability for the defense and nondefense sectors. The results using multivariate maximum likelihood techniques found that ther is clear hierarchy of employee involvement programs that are used within firms. However, having higher levels of employee involvement among firms is not significantly related to higher levels of productivity.

A second paper that was given at the American Economic Association meeting during January 1998 examined the role of employee involvement on changes in manufacturing productivity for both defense and nondefense-related manufacturing plants. Among the unique aspects of this study is the use of matched plants by product line. The method examines plants that had employee involvement to those that did not. The results are inconclusive regarding the impact of employee involvement on manufacturing productivity over time.

The third paper was presented at the American Compensation Association research conference during March 1998. This paper examined the impact of a firm with defense-related operations changing its method of compensation from piece-rate to time-rate methods of pay. The study attempts to examine the impact of the change in the pay incentive system on the performance of the plant that switched its method of pay overtime and also relative to those that did not. The results show that productivity dropped but that savings in other areas such as worker compensation insurance and reductions in inventory resulted in no effects on plant level measures of profitabili

5. **Information and High-Technology in the Design of U.S. Foreign Economic Policy – Robert T. Kudrle**

This subproject explored a number of national security and prosperity issues related to information, technology, and resource control in an increasingly open and interdependent global economy.

During the first year of the grant Professor Kudrle made progress in several areas dealing with information about technology flows in and out of the United States. His paper, with his University of Pittsburgh colleague, Davis Bobrow, "Should the U.S. Spy for Competitiveness?" explores various policy options the United States faces in dealing with foreign industrial espionage, with or without state support. (A longer version of this paper was called "International Espionage for Commercial Advantage.")

A later paper, "Foreign Acquisition of Defense-Related U.S. Firms: Concentration, Competition, and Reality," examined the logical and evidentiary foundation for some of the proposed improvements in the Exon-Florio Amendment to the Trade Act of 1988. Specifically, the paper criticizes the adequacy of proposals that look at only one or two aspects of a defense-related market as an indicator of the dangers or innocuousness of foreign acquisition. The paper argues strongly that there are no simple rules assuring safety in defense acquisition. This flatly contradicts suggestions that rules be based on measures of industrial concentration. The paper argues that attention to the nationality of the acquiring firm is also essential for sound policy.

In the second year of the grant Professor Kudrle published a broader view of the American economy in its global context in "Three Perspectives on U.S. Competitiveness." The paper concurs with Krugman's analysis that the American economic problem is one of productivity, not "competitiveness" by exploring three different meanings of the latter term in the literature: firm competitiveness, industry competitiveness, and national competitiveness. This study and the defense acquisition paper noted earlier suggest that a focus on inadequate economic information in the hands of the U.S. government may not be the generally serious problem (at least relative to other states) that Laura Tyson implied in her 1992 book, Who's Bashing Whom: Trade Conflict in High Technology Industries. Nevertheless, some information gaps loom for years after being identified. Perhaps chief among them is the absence of detailed information abut subcontractors supplying the Departments of Defense and Energy.

A major cluster of research during the grant's second year turned on the concept of "globalization" and its implications for U.S. security and welfare. The paper "Globalization and the Future Policies of the Industrial States" was delivered at the annual meeting of the International Studies Association in San Diego in March. It argues that the losses of national control of economy destiny that are widely claimed by exponents of globalization are largely a mixture of the premature and the misunderstood. In particular, long-term capital is not anything like as mobile as is sometimes claimed (because it is confused with speculative short-term capital movements.) Only when capital mobility increases will countries find it necessary to moderate their capital taxation rates to avoid losing capital to other states. The same argument applies to skilled labor. Moreover, when capital mobility does increase – probably as the result of increased fixity of exchange rates – the amount of international cooperation necessary to keep states from competing with each other for resources should be quite modest. The immigration of unskilled labor probably represents the greatest current threat to prosperity from the phenomena generally associated with the term globalization. The revised version of this paper was presented at a conference at Indiana University in October of 1996. A related paper on "The Continuing Uses of Economic Nationalism," was presented at a joint meeting of the Japan Association of International Relations and the International Studies Association, held in Tokyo in September, 1996. This paper stressed the continuing value of economic nationalism in some areas, especially immigration, while noting that most economic nationalism lowers the welfare of the state's citizens. A third related work on the alternative meanings of "globalization" and their public policy implications was presented at a conference at the University of Notre Dame in April of 1997.

All this research was conducted with a common theme in mind: what are the information requirements and policy directions that maximize U.S. prosperity and security in a world economy of constant change?

The third year of the grant continued the major cluster of research identified as "globalization" and its implications for U.S. prosperity and security. Professor Kudrle presented a paper on fiscal issues connected with globalization at the conference, "Coping with Globalization" in July 1998. Some argue that inter-state competition resulting from globalization has removed the state's capacity to tax its citizens and enterprises at levels consonant with domestic welfare. Professor Kudrle's paper argued that there is little evidence that this is the case, and that taxation levels in the United States and elsewhere continue to be governed mainly by purely domestic processes, although those favoring certain policy directions, e.g., lower rates of tax on capital, are happy to invoke international considerations to argue that the preferences are really driven by external constraints.

With Davis Bobrow, Professor Kudrle extended grant activities in the direction of information and security problems in regional integration schemes. They presented the paper "APEC as partisan Mutual Adjustment: Foreign Direct Investment and Competition Policies" at the Seventeenth World Congress of the International Political Science Association in Seoul, Korea, August 7-21, 1997. Much of the summer of 1997 was also involved in the preparation of another paper that was presented in Manzanillo, Mexico, December 11, 1997. This work carefully examined the national interest issues connected with competition policy when states move closer together in regional integration schemes.

Papers resulting from grant funding:

"Three Perspectives on Competitiveness: An Introduction to 'Made In America,'" The International Executive, July/August, 1996.

"Should the U.S. Spy for Competitiveness?" (with Davis B. Bobrow), Business and the Contemporary World, VIII, 3-4, 1996.

"Economic Nationalism and the Global Economy," in Iliana Zloch-Christy, ed., Eastern Europe and the World Economy: Challenges of Transition and Globalization, Edward Elgar Publishing, 1997.

"Immigration Policy and National Prosperity," Framtider International, July-August 1997.

"Foreign Acquisition of Defense-Related U.S. Firms: Concentration, Competition and Reality," (with Davis B. Bobrow), in Douglas Nigh and Douglas Woodward, eds., Beyond "Us" and "Them": Foreign Ownership and U.S. Competitiveness, Quorum Press, 1998.

"Competition Policy and Regional Integration: Compatibility and Conflict," (with Davis B. Bobrow) Journal of International Political Economy, March 1998.

"Globalization and the Politics of the Future," in Jeffrey Hart and Aseem Prakash, eds., Globalization and Governance, Routledge, forthcoming.

"APEC as Partisan Mutual Adjustment" (with Davis B. Bobrow) in Mary Ann Tetreault and Kenneth Thomas, eds., Regionalism and Global Political Economy, Lynne Rienner Publishers, forthcoming.

"International Espionage for Commercial Advantage," (with Davis B. Bobrow) in Stuart S. Nagel, ed. Studies in Public Policy Analysis and Management, St. Martin's Press, forthcoming.

"Three Meanings of Globalization and Their Implications for Governance," in Global Governance and Enforcement: Issues and Strategies, Raimo Väyrynen, ed., Rowman and Littlefield, forthcoming.

"Aruba and the Challenge of Globalization," Proceedings of the Third Aruba Economic Summit, Aruba: Ministry of Economic Affairs, forthcoming.

"Does Globalization Sap the Fiscal Power of the State?" in Aseem Prakash and Jeffrey Hart, eds. Coping With Globalization, manuscript in preparation.

"Investment and Competition Policies in Regional Perspective (with Davis B. Bobrow),presented at the International Studies Association and the Pan-European International Relations

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A comparison of what we intended to accomplish with grant funding and what was actually produced gives us much satisfaction. In each of the subprojects, more was delivered than was promised, and we believed that the funding provided was a sound national investment.

Final Report for the AFOSR Contract AF/F49620-94-1-0461 entitled "New Priorities in a Changing US Economy"

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1 Introduction

In the research program supported by AF/F49620-94-1-0461 we have carried out an extensive program in image processing, vision, and control. Our methodologies have been applied to certain benchmark problems involving visual tracking.

We have been working as well in distributed parameter control as part of the sponsored research. Recently a monograph [44] which extensively describes our *skew Toeplitz* approach to distributed H^∞ design and analysis has been published. We have also explored problems in μ-synthesis and analysis. Our results work directly for systems, not just finite matrices. This allows us to study broad classes of structured perturbations using this tool. We have also been continuing our work for a rigorous μ–synthesis procedure based on structured interpolation.

We have applied our methods to the key area of visual tracking which may be employed for a number of problems in robotics, manufacturing, As alluded to above, we have developed robust control algorithms valid for general classes of distributed parameter and nonlinear systems based on interpolation and operator theoretic methods. In this project, we have been explicitly combining our robust control techniques with our novel approach to image processing in order to develop novel visual tracking algorithms.

In active vision, we have been conducting research into advanced algorithms in image processing and computer vision for a variety of uses: image smoothing and enhancement, image segmentation, morphology, denoising algorithms, shape recognition, edge detection, optical flow, shape-from-shading, and deformable contours ("snakes"). Our techniques have already been applied to medical imaging, and have been used to define a novel affine invariant scale-space. Our ideas are motivated by certain types of geometric invariant flows rooted in the mathematical theory of curve and surface evolution. There are now available powerful numerical algorithms based on Hamilton-Jacobi type equations and the associated theory of viscosity solutions for the computer implementation of this methodology. In addition to systems and control, our work in vision can also has had an impact on ATR. This is based on the nonlinear filters we have developed for image enhancement that are natural corollaries of our work. These filters can smooth while preserving such key features as edges and ridges.

2 Structured Perturbations

We have investigated a number of the key properties of the *structured singular value* which was introduced into robust control by John Doyle and Michael Safonov ([34], [85]) to handle problems involving structured perturbations which includes both H^∞ and the multivariable gain margin as special cases. In particular, we have introduced a new *lifting* or *ampliation* method for the study of robustness under a variety of structured perturbation models. We will now briefly elucidate some of the key results in this area. Details about this methodology can be found in our papers [19, 17, 18, 25, 20].

2.1 Preliminary Results on Structured Singular Values

In this section, we will introduce some notation and elementary results about the structured singular value which we will need to explain our ampliation method.

Let A be a linear operator on a Hilbert space $\mathcal{E}$, and let Δ be an algebra of operators on $\mathcal{E}$. The *structured singular value* of A (relative to Δ) is the number

$$\mu_\Delta(A) = 1/\inf\{\|X\| : X \in \Delta,\ -1 \in \sigma(AX)\}\,.$$

(This quantity was defined in [34, 85] under a more restrictive context.) Recall that in system analysis, the structured singular value gives a measure of robust stability with respect to certain perturbation measures. Unfortunately, $\mu_\Delta(A)$ is very difficult to calculate, and in practice an upper bound for it is used. This upper bound is defined by

$$\widehat{\mu}_\Delta(A) := \inf\{\|XAX^{-1}\| : X \in \Delta', X \text{ invertible}\},$$

where Δ' is the commutant of the algebra Δ.

In [23, 20], we formulated a lifting technique for the study of the structured singular value. The basic idea is that $\widehat{\mu}_\Delta(A)$ can be shown to be equal to the structured singular value of an operator on a bigger Hilbert space. (In [23] this was done for finite dimensional Hilbert spaces, and then in [20] this was extended to the infinite dimensional case.) The problem with these results is that the size of the ampliation necessary to get $\widehat{\mu}_\Delta(A)$ equal to a structured singular value, was equal to the dimension of the underlying Hilbert space. Hence in the infinite dimensional case we needed an infinite ampliation. We should note, that one important result that came out of the work in [23] was that for the first time the upper bound $\widehat{\mu}$ was shown to be *continuous*. Since this is the quantity actually used in μ analysis and synthesis, this result is certainly of importance.

In our most recent work [19], we have shown that in fact, one can always get by with a finite ampliation. For the block diagonal algebras of interest in robust control, the ampliation only depends on the number of blocks of the given perturbation structure. We will moreover, give a new criterion below showing when $\widehat{\mu}_\Delta(A) = \mu_\Delta(A)$, that is, when no lifting is necessary and so $\widehat{\mu}_\Delta(A)$ gives a *nonconservative measure of robustness*. This is then used to derive an elegant result of Megretski and Shamma [71, 94] on Toeplitz operators.

We will denote by $\mathcal{L}(\mathcal{E})$ the algebra of all bounded linear operators on the (complex, separable) Hilbert space $\mathcal{E}$. Fix an operator $A \in \mathcal{L}(\mathcal{E})$ and a subalgebra $\Delta \subset \mathcal{L}(\mathcal{E})$. Observe that $\Delta \subset \Delta''$ and $\Delta''' = (\Delta'')' = \Delta'$ so that we have the inequalities

$$\mu_\Delta(A) \leq \mu_{\Delta''}(A), \quad \widehat{\mu}_\Delta(A) = \widehat{\mu}_{\Delta''}(A) \ .$$

In our study we will need further singular values which we now define. For $n \in \{1, 2, \ldots, \infty\}$ we denote by $\mathcal{E}^{(n)}$ the orthogonal sum of n copies of $\mathcal{E}$, and by $T^{(n)}$ the orthogonal sum of n copies of $T \in \mathcal{L}(\mathcal{E})$. Operators on $\mathcal{E}^{(n)}$ can be represented as $n \times n$ matrices of operators in $\mathcal{L}(\mathcal{E})$, and $T^{(n)}$ is represented by a diagonal matrix, with diagonal entries equal to T.

Denote by Δ_n the algebra of all operators on $\mathcal{E}^{(n)}$ whose matrix entries belong to Δ, and observe that $(\Delta_n)'' = (\Delta'')_n$, and $(\Delta_n)' = (\Delta')^{(n)} = \{T^{(n)} : T \in \Delta'\}$. Therefore we will denote these algebras by Δ''_n and Δ'_n, respectively.

We can now formulate our lifting result from [19], relating $\mu_\Delta(A)$ and $\widehat{\mu}_\Delta(A)$. For finite dimensional $\mathcal{E}$, a lifting result of this type was first proven in [23]. The result was then generalized to the infinite dimensional case in [20]. In these previous works, the lifting or ampliation of the operator A and perturbation structure Δ depends on the dimension of $\mathcal{E}$. Thus if $\mathcal{E}$ is infinite dimensional, we get an infinite lifting. In Theorem 1 stated below, we only have to lift up to the dimension of Δ' which in the cases of interest in the control applications of this theory only depends on the number of blocks of the given perturbation structure. The proof of the theorem makes use of some work that we did on the *relative numerical range* and the continuity of the spectrum on closed similarity orbits in [17, 18] which we believe also has independent interest.

Theorem 1 *Assume that Δ' is a $*$-algebra of finite dimension n. Then*

$$\widehat{\mu}_\Delta(A) = \mu_{\Delta''_n}(A^{(n)})$$

for every $A \in \mathcal{L}(\mathcal{E})$.

Remark. In the cases of interest in control,

$$\Delta'' = \Delta,$$

and so one has from Theorem 1 that

$$\mu_{\Delta_n}(A) = \hat{\mu}_\Delta(A).$$

2.2 Conditions for $\mu = \widehat{\mu}$

We will discuss some the conditions from [19] when $\mu = \widehat{\mu}$ without any need for lifting or ampliation. In such cases, $\widehat{\mu}$ gives a nonconservative measure of robustness relative to the given perturbation structure. In the finite dimensional case, there have been some results of this kind, the most famous of which is that of Doyle [34], who showed that no lifting is necessary for perturbation structures with three or fewer blocks.

First of all, call *critical* any $A_0 \in \overline{\mathcal{O}_{\Delta'}(A)}$ satisfying

$$\limsup_{\epsilon \downarrow 0} \|(I - \epsilon X)A_0(I - \epsilon X)^{-1}\| \geq \|A_0\|, \ \forall X \in \Delta'.$$

Then we have

Lemma 1 *If A_0 is a critical operator in $\overline{\mathcal{O}_{\Delta'}(A)}$, then it enjoys the following property* $(\mathcal{O})$:

$$0 \in W_Q(\|A_0\|^2 X - A_0^* X A_0),\ X \in \Delta',$$

where $Q = \|A_0\|^2 I - A_0^* A_0$.

The next lemma is the key step in adapting the proof of Theorem 1 in order to show that

$$\mu_\Delta(A) = \widehat{\mu}_\Delta(A)$$

in several interesting cases.

Lemma 2 *Let A_0 be an operator on $\mathcal{E}$ which satisfies the essential version of property* $(\mathcal{O})$, *property* $(\mathcal{O}^0)$, *namely*

$$0 \in W_Q^0(\|A_0\|^2 X - A_0^* X A_0),\ X \in \Delta',$$

where $Q = \|A_0\|^2 I - A_0^* A_0$. Then there exists a sequence $\{h_k\}_{k=1}^{\infty} \subset \mathcal{E}$, $\|h_k\| = 1$, $k = 1, 2, \ldots$, such that

$$Qh_k \to 0 \text{ strongly and } \langle(\|A_0\|^2 X - A_0^* X A_0)h_k, h_k\rangle \to 0,$$

for all $X \in \Delta'$.

We can now state another key result:

Theorem 2 *If there exists a critical operator A_0 satisfying property $\mathcal{O}^0$ in the closed Δ'-orbit of A, then*

$$\mu_{\Delta''}(A) = \widehat{\mu}_\Delta(A).$$

Remark. Under the hypotheses of Theorem 2, when $\Delta'' = \Delta$ (which happens in all cases of interest in control), we have that

$$\mu_\Delta(A) = \widehat{\mu}_\Delta(A).$$

Let $L(\Delta' A \Delta')$ denote the linear space generated by

$$\Delta' A \Delta' = \{XAY : X, Y \in \Delta'\}.$$

Obviously $L(\Delta' A \Delta')$ is finite dimensional, and therefore closed. Hence $\overline{\mathcal{O}_{\Delta'}(A)} \subset L(\Delta' A \Delta')$.

Corollary 1 *If for every $B \in L(\Delta' A \Delta')$, $B \neq 0$, the norm of B is not attained (that is, there is no $h \in \mathcal{H}$ such that $\|Bh\| = \|B\|\|h\| \neq 0$), then*

$$\mu_{\Delta''}(A) = \widehat{\mu}_\Delta(A).$$

3 Nonlinear Control

In our work in nonlinear robust control, and especially the extension of H^∞ to the nonlinear framework, we have discovered a number of intriguing problems which do not occur in the linear case. Indeed, besides the theoretical and practical questions involved in finding an implementable design methodology, it is interesting to note that certain associated problems of causality have arisen in working in this area, which we would like to briefly sktch. In fact, as a result of this effort we have been able to put an explicit causality constraint in commutant lifting theory for the first time [40, 42, 48, 16].

There have been several attempts to extend dilation theoretic techniques to nonlinear input/output operators, especially those which admit a Volterra series expansion (see [41] and the references therein). In several of these approaches, one is reduced to applying the classical (linear) commutant lifting theorem to an H^2-space defined on some D^n (where D denotes the unit disc). Now when one applies the classical result to D^n ($n \geq 2$), even though time-invariance is preserved (that is, commutation with the appropriate shift), causality may be lost. Indeed, for analytic functions on the disc D, time-invariance (that is, commutation with the shift) implies causality. For analytic functions on the $n-$disc ($n > 1$), this is not necessarily the case. For dynamical system control design and for any physical application, this is of course a major drawback. Hence for a dilation result in $H^2(D^n)$ we need to include the causality constraint explicitly in the set-up of the dilation problem. We will discuss a way of doing this now based on [48, 41, 42].

3.1 Causality in Nonlinear Systems

Causality basically means that for a given input/output system the past output is independent of the future inputs. This may be given precise mathematical formulation in terms of a family of projections which we shall now do. We follow treatment of [48].

Let S denote an isometry on a Hilbert space $\mathcal{G}$, and let T denote a contraction on a Hilbert space $\mathcal{H}$. Let P_{j0}, $j \geq 1$ denote a sequence of orthogonal projections in $\mathcal{G}$ satisfying the following conditions:

$$\begin{aligned} P_{10} &\leq P_{20} \leq \dots && (1)\\ P_{j0} &\leq I - S^j S^{*j} \quad j = 1, 2, \dots && (2)\\ P_{j+1,0} S (I - P_{j0}) &= 0 \quad j = 1, 2, \dots. && (3) \end{aligned}$$

Next $U : \mathcal{K} \to \mathcal{K}$ will denote a minimal isometric dilation of the given contraction T defined on $\mathcal{H}$. Let $B : \mathcal{G} \to \mathcal{H}$ intertwine S with U, that is,

$$UB = BS. \tag{4}$$

Note that this latter condition implies $U^j B = B S^j$ ($j \geq 1$), hence $U^j U^{*j} B S^j S^{*j} = B S^j B^{*j}$, and so

$$(I - U^j U^{*j}) B = (I - U^j U^{*j}) B (I - S^j S^{*j}) \quad j = 1, 2, \dots. \tag{5}$$

We now make the following key definition:

Definition. An operator B satisfying (4) is called $(P_{10}, P_{20}, \ldots)$-*causal* (and if the sequence $\{P_{j0}\}_{j=1}^{\infty}$ is fixed, *causal*) if

$$(I - U^j U^{*j})B = (I - U^j U^{*j})BP_{j0} \quad j \geq 1, \tag{6}$$

or equivalently,

$$(I - P_{j0})B^* = (I - P_{j0})B^* U^j U^{*j} \quad j \geq 1. \tag{7}$$

Note that B is always $(I - SS^*, I - S^2 S^{*2}, \ldots)$-causal. In what follows the sequence $P_{10}, P_{20}, \ldots$ will be fixed and causality will always be defined relative to this sequence.

Next we let $A : \mathcal{G} \to \mathcal{H}$ be an operator intertwining S and T, that is, $AS = TA$. Then an *intertwining lifting (or dilation) of* A is an operator $B : \mathcal{G} \to \mathcal{K}$ such that $BS = UB$, and $PB = A$ where $P : \mathcal{K} \to \mathcal{H}$ denotes orthogonal projection.

We define

$$\nu_\infty(A) := \inf\{||B|| : B \text{ is a causal intertwining dilation of } A\},$$

and

$$\mu(A) := \min\{M \geq 0 : ||A|| \leq M,\ ||(I - P_{j0})A^* h|| \leq M||T^{*j}h||,\ h \in \mathcal{H}\ j \geq 1\}.$$

We can then show that

$$\mu(A) \leq \nu_\infty(A). \tag{8}$$

We will also need a functional which lies between $\mu(A)$ and $\nu_\infty(A)$. To this aim, we call a sequence of operators $\Gamma_j : \mathcal{G}_j := (I - P_{0j})\mathcal{G} \to \mathcal{H}$, $j = 0, 2, \ldots$ a *resolution of* A if

$$\begin{aligned}
\Gamma_0 &= A \\
\Gamma_j|\mathcal{G}_{j+1} &= T\Gamma_{j+1} \quad \forall j \geq 0, \\
\Gamma_j &= \Gamma_{j+1}S|\mathcal{G}_j \quad \forall j \geq 0.
\end{aligned}$$

(Note that we take $P_{00} := 0$, so that $\mathcal{G}_0 = \mathcal{G}$.) We now define

$$\tilde{\mu}(A) :=$$

$$\min\{M \geq 0 : ||A|| \leq M \text{ and there exists a resolution of } A,\ \Gamma_j, \text{ with } ||\Gamma_j|| \leq M,\ \forall j \geq 0\}.$$

Then, we have the following results from [48]:

Theorem 3 (Causal Commutant Lifting Theorem) *Notation as above. Then*

$$\nu_\infty(A) = \tilde{\mu}(A).$$

3.2 Iterated Nonlinear Optimization

We will now consider, how the above ideas, lead to a an optimization procedure for nonlinear systems which generalizes H^∞ in a completely natural manner. For convenience, we will only treat SISO systems here. Let us call an analytic input/output operator $\phi : H^2 \to H^2$ *admissible* if is is causal, time-invariant, majorizable, and $\phi(0) = 0$. Denote the set of admissible operators by $\mathcal{C}_a$. In what follows below, we assume $P, W \in \mathcal{C}_a$, and that W admits an admissible inverse.

We consider the (one block) problem of finding

$$\mu_\delta := \inf_{C} \sup_{\|v\| \leq \delta} \|[(I + P \circ C)^{-1} \circ W]v\|, \tag{9}$$

where we take the infimum over all stabilizing controllers. (In what follows, we let $\| \ \|$ denote the 2-norm $\| \ \|_2$ on H^2 as well as the associated operator norm. The context will make the meaning clear.) Thus we are looking at a worst case disturbance attenuation problem where the energy of the signals v is required to be bounded by some pre-specified level δ. (In the linear case of course since everything scales, we can always without loss of generality take $\delta = 1$. For nonlinear systems, we must specify the energy bound *a priori*.) Then one sees that (9) is equivalent to the problem of finding the problem of finding

$$\mu_\delta = \inf_{q \in \mathcal{C}_a} \sup_{\|v\| \leq \delta} \|(W - P \circ q)v\|. \tag{10}$$

The iterated causal commutant lifting procedure gives an approach for approximating a solution to such a problem. Briefly, the idea is that we write

$$\begin{aligned} W &= W_1 + W_2 + \cdots, \\ P &= P_1 + P_2 + \cdots, \\ q &= q_1 + q_2 + \cdots, \end{aligned}$$

where W_j, P_j, q_j are homogeneous polynomials of degree j. Notice that

$$\mu_\delta = \delta \inf_{q_1 \in H^\infty} \|W_1 - P_1 q_1\| + O(\delta^2), \tag{11}$$

where the latter norm is the operator norm (i.e., H^∞ norm). From the classical commutant lifting theorem we can find an optimal (linear, causal, time-invariant) $q_{1,opt} \in H^\infty$ such that

$$\mu_\delta = \delta \|W_1 - P_1 q_{1,opt}\| + O(\delta^2). \tag{12}$$

Now the iterative procedure gives a way of finding higher order corrections to this linearization. Let us illustrate this now with the second order correction. Indeed, having fixed the linear part $q_{1,opt}$ of q in (10), we note that

$$W(v) - P(q(v)) - (W_1 - P_1 q_{1,opt})(v) =$$

$$W_2(v) - P_2(q_{1,opt}(v)) - P_1 q_2(v) + \text{higher order terms.}$$

Regarding W_2, P_2, q_2 as linear operators on $H^2 \otimes H^2 \cong H^2(D^2, \mathbf{C})$ as above, we see that

$$\sup_{\|v\| \leq \delta} \|(W - P \circ q)(v) - (W_1 - P_1 q_{1,opt})v\| \leq \delta^2 \|\hat{W}_2 - P_1 q_2\| + O(\delta^3),$$

where the "weight" $\hat{W}_2$ is given by

$$\hat{W}_2 := W_2 - P_2(q_{1,opt} \otimes q_{1,opt}).$$

Using the control version of the causal commutant lifting theorem (see [41] and Section 4.1 below), we can now construct an optimal admissible $q_{2,opt}$, and so on. This is our *iterated optimization procedure.*

In short, instead of simply designing a linear compensator for a linearization of the given nonlinear system, this methodology allows one to explicitly take into account the higher order terms of the nonlinear plant, and therefore increase the ball of operation for the nonlinear controller. Moreover, if the linear part of the plant is rational, our iterative procedure may be reduced to a series of finite dimensional matrix computations. (See [41, 45] for discussions of rationality in the nonlinear framework.)

4 Curve Evolution in Vision

In the past few years, we have become very interested in visual tracking and the general area of the use of visual information in a feedback loop. This is a central area in which the robust control methods developed over the past fifteen years could have a major impact. In order to work on visual tracking, we have had to learn some of the key techniques from image processing and computer vision, which has led in turn to a new research direction. Indeed, we have been using geometric invariant flows for various problems in active vision. These flows themselves are very much motivated by ideas in optimal control; see [65]. We will now discuss some of the key ideas in curve evolution. These will be applied to certain problems in controlled active vision as described below.

4.1 Curve Evolution

A geometric set or shape can be defined by its boundary. In the case of bounded planar shapes for example, this boundary consists of closed planar curves. We will only deal with closed planar curves, keeping in mind that these curves are boundaries of planar shapes.

A curve may be regarded as a trajectory of a point moving in the plane. Formally, we define a curve $\mathcal{C}(\cdot)$ as the map $\mathcal{C}(p) : S^1 \to \mathbf{R}^2$ (where S^1 denotes the unit circle). $\mathcal{C}$ can be written using Cartesian coordinates, i.e., $\mathcal{C}(p) = [x(p), y(p)]^T$, where $x(\cdot)$ and $y(\cdot)$ are maps from S^1 to $\mathbf{R}$. We assume that all of our mappings are sufficiently smooth, so that all the relevant derivatives may be defined. We also assume that our curves are have no self-intersections, i.e., are embedded.

We now consider plane curves deforming in time. Let $\mathcal{C}(p,t) : S^1 \times [0,\tau) \to \mathbf{R}^2$ denote a family of closed embedded curves, where t parametrizes the family, and p parametrizes each curve. Assume that this family evolves according to the following equation:

$$\begin{cases} \frac{\partial \mathcal{C}}{\partial t} = \alpha \vec{\mathcal{T}} + \beta \vec{\mathcal{N}} \\ \mathcal{C}(p,0) = \mathcal{C}_0(p) \end{cases} \tag{13}$$

where $\vec{\mathcal{N}}$ is the inward Euclidean unit normal, $\vec{\mathcal{T}}$ is the unit tangent, and α and β are the tangent and normal components of the evolution velocity $\vec{v}$, respectively. In fact, it is easy to show that $\mathrm{Img}[\mathcal{C}(p,t)] = \mathrm{Img}[\hat{\mathcal{C}}(w,t)]$, where $\mathcal{C}(p,t)$ and $\hat{\mathcal{C}}(w,t)$ are the solutions of

$$\mathcal{C}_t = \alpha \vec{\mathcal{T}} + \beta \vec{\mathcal{N}} \text{ and } \hat{\mathcal{C}}_t = \bar{\beta} \mathcal{N},$$

respectively. (Here Img[$\cdot$] denotes the image of the given parametrized curve in $\mathbf{R}^2$.) Thus the tangential component affects only the parametrization, and not Img[$\cdot$] (which is independent of the parametrization by definition). Therefore, assuming that the normal component β of $\vec{\nu}$ (the curve evolution velocity) in (13) does not depend on the curve parametrization, we can consider the evolution equation

$$\frac{\partial \mathcal{C}}{\partial t} = \beta \vec{\mathcal{N}}, \tag{14}$$

where $\beta = \vec{\nu} \cdot \vec{\mathcal{N}}$, i.e., the projection of the velocity vector on the normal direction.

The evolution (14) was studied by different researchers for different functions β. This type of flow was introduced into the theory of shape in [61, 62, 63, 64]. One of the most studied evolution equations is obtained for $\beta = \kappa$, where κ is the Euclidean curvature:

$$\frac{\partial \mathcal{C}}{\partial t} = \kappa \vec{\mathcal{N}}. \tag{15}$$

Equation (15) has its origins in physical phenomena [3, 53]. It is called the *Euclidean shortening flow*, since the Euclidean perimeter shrinks as fast as possible when the curve evolves according to (15); see [53]. Gage and Hamilton [51] proved that a planar embedded convex curve converges to a round point when evolving according to (15). (A round point is a point that, when the curve is normalized in order to enclose an area equal to π, it is equal to the unit disk.) Grayson [52] proved that a planar embedded non-convex curve converges to a convex one, and from there to a round point from Gage and Hamilton result. Note that in spite of the local character of the evolution, global properties are obtained, which is a very interesting feature of this evolution. For other results related to the Euclidean shortening flow, see [3, 4, 51, 52, 53, 64, 102].

Next note that if s denotes the Euclidean arc-length, then

$$\kappa \vec{\mathcal{N}} = \frac{\partial^2 \mathcal{C}}{\partial s^2}.$$

Therefore, equation (15) can be written as

$$\mathcal{C}_t = \mathcal{C}_{ss}. \tag{16}$$

Equation (16) is not linear, since s is a function of time (the arc-length gives a time dependent parametrization). This equation is also called the *geometric heat equation.*

Another interesting example is obtained when one sets $\beta = 1$ in equation (14). This equation simulates, under certain conditions, the grassfire flow [27, 61, 62, 64, 92]. This grassfire flow is also the morphological scale-space created by a disk. One can show that with different selections of β, other morphological scale-spaces are obtained [65].

In [61, 62, 64], we have studied the following equation in order to develop a hierarchy of shape,

$$\frac{\partial \mathcal{C}}{\partial t} = (1 + \epsilon\kappa) \vec{\mathcal{N}}. \tag{17}$$

If $\epsilon \to 0$ in (17), the grassfire flow is obtained, and this introduces singularities (*shocks*) in the evolving curve. (The shocks define the well-known skeleton.) On the other hand, if $\epsilon \to \infty$, equation (17) reduces to the classical Euclidean curve shortening flow, which smoothes the curve [52, 93]. The combination of these two opposite features gives very interesting properties [61].

When a curve evolves according to (17), the evolution of the curve slope satisfies a reaction-diffusion equation [95]. The reaction term, which tends to create singularities, competes with the diffusion term which tends to smooth the curve. For each different value of ϵ, a scale-space is obtained by looking at the solution of (17), and considering the time t as the scale parameter. We have called the set of all the scale-spaces obtained for all values of ϵ, the *reaction-diffusion scale-space* [62]. In particular, we see that the much studied Euclidean shortening flow (equation (15)) defines an Euclidean invariant scale-space (the equation admits Euclidean invariant solutions).

We now discuss the affine analogue of the Euclidean shortening flow. (The affine group SA_2 is the group generated by unimodular transformations and translations of $\mathbf{R}^2$. Under certain natural conditions, it provides a good approximation to the full group of perspective projective transformations.) Then in [77, 87], we show that the simplest non-trivial affine invariant flow in the plane is given by

$$\mathcal{C}_t = \kappa^{1/3}\vec{\mathcal{N}}. \tag{18}$$

The question now is what happens when a non-convex curve evolves according to (18). The following result answers this question [5]:

Theorem 4 *Let $\mathcal{C}(\cdot,0) : S^1 \to \mathbf{R}^2$ be a smooth embedded curve in the plane. Then there exists a family $\mathcal{C} : S^1 \times [0,T) \to \mathbf{R}^2$ satisfying*

$$\mathcal{C}_t = \kappa^{1/3}\vec{\mathcal{N}},$$

such that $\mathcal{C}(\cdot,t)$ is smooth for all $t < T$, and moreover there is a $t_0 < T$ such that for all $t > t_0$, $\mathcal{C}(\cdot,t)$ is smooth and convex.

Theorem 4 means that just as in the Euclidean case, a non-convex curve first becomes convex when evolving according to (18). After this, the curve converges to an ellipse from our results in [87]. Because of this, and other related properties (see [88]), we can conclude that equation (18) is the affine analogue of (15) for smooth embedded curves, and thus is called the *affine shortening flow.* (It is also the affine invariant formulation of the geometric heat equation.) In the next section, we will use it to construct an *affine invariant scale-space* for planar shapes.

4.2 Affine invariant scale-space

In the previous section, we indicated that equation (18) is the affine analogue of (15). Of course, in addition to the Euclidean invariant property of the Euclidean curve shortening flow, this affine flow admits also unimodular affine invariant solutions. Due to this analogy, and certain key properties [88], we can use the affine shortening flow for defining a new *affine invariant scale-space.* More precisely, the representation of shape obtained from the evolving solution of equation (18), defines the affine invariant scale-space. The scale parameter is given by the time t

Note the curve shrinks when evolving according to (18). This curve can be normalized in order to keep constant area. In fact, in [89], we have evolutions that preserve either area or length. The affine scale-space can therefore be re-defined by means of these normalized dilated curves. Since the process of normalization modifies κ, and other geometric properties just by constant multiplication [87], all the key scale-space features for the family of curves C satisfying (18), also hold for the normalized scale-space.

When defining scale-spaces, a number of desired properties must be verified [56, 66, 80, 103]. One of the most important properties is the *causality criterion*, which requires that no new features should be introduced in the curve (or image) in passing from fine to coarse scales in the scale-space. In general, "features" are related to the salient characteristics of the signal, which are important for the image description, and are easily identified.

Hummel in [56] showed that the causality criterion may be expressed in terms of the Maximum Principle [82]. The Maximum Principle states that under certain conditions, a given function satisfying a parabolic partial differential equation, attains its maximum (minimum) on the boundary [82]. (The Maximum Principle is very frequently used in the theory of curve evolution for proving important properties.) Hummel showed that under certain conditions, when the Maximum Principle holds for a given parabolic operator, which defines the scale-space, zero-crossings are never created at a non-zero scale. (This result was used in [80] for demonstrating the causality principle.) In our work [5, 88], we show that the affine shortening flow satisfies a Maximum Principle, and so because of this and other related properties, the affine invariant scale-space is an ideal vehicle for the multi-scale study of shape.

4.3 Visual Tracking

Much of our recent research in image processing and computer vision has been motivated by problems in controlled active vision, especially visual tracking. We have already described some of the relevant work in control above, and so we would like to consider now some of the key tools we plan to employ from our work in computer vision and image processing. These include active contours, optical flow and stereo disparity, and certain results from invariant theory for invariant object recognition, as well as the curve and surface evolution methodology sketched above in Section 4. These methods have played an integral part in our study of the utilization of visual information in a feedback loop.

4.4 Geometric Active Contours

In this section, we will describe a new paradigm for *snakes* or *active contours* based on principles from geometric optimization theory. Active contours may be regarded as autonomous processes which employ image coherence in order to track various features of interest over time. Such deformable contours have the ability to conform to various object shapes and motions. Snakes have been utilized for segmentation, edge detection, shape modeling, and visual tracking. Active contours have also been widely applied for various applications in medical imaging. For example, snakes have been employed for the segmentation of myocardial heart boundaries as a prerequisite from which such vital information such as ejection-fraction ratio, heart output, and ventricular volume ratio can be computed.

In the classical theory of snakes, one considers energy minimization methods where controlled continuity splines are allowed to move under the influence of external image dependent forces, internal forces, and certain contraints set by the user. As is well-known there may be a number of problems associated with this approach such as initializations, existence of multiple minima, and the selection of the elasticity parameters. Moreover, natural criteria for the splitting and merging of contours (or for the treatment of multiple contours) are not readily available in this framework.

In [60], we have proposed a novel deformable contour model to successfully solve such problems, and which will become one of our key techniques for tracking. Our method is based on the Euclidean curve shortening evolution (see Section 4.1) which defines the gradient direction in which a given curve is shrinking as fast as possible relative to Euclidean arc-length, and on the theory of conformal metrics. Namely, we multiply the Euclidean arc-length by a function tailored to the features of interest which we want to extract, and then we compute the corresponding gradient evolution equations. The features which we want to capture therefore lie at the bottom of a potential well to which the initial contour will flow. Further, our model may be easily extended to extract 3D contours based on motion by mean curvature [60].

We first choose a function $\phi(x, y)$ which depends on the given image and is used as a "stopping term." For example, the term $\phi(x, y)$ may chosen to be small near an edge, and so acts to stop the evolution when the contour gets close to an edge. One may take

$$\phi := \frac{1}{1 + ||\nabla G_\sigma * I||^2}, \tag{19}$$

where I is the (grey-scale) image and G_σ is a Gaussian (smoothing filter) filter.

Using ϕ, we now define our geometric snake algorithm based on ideas from Euclidean curve shortening. Indeed, we will change the ordinary Euclidean arc-length function along a curve $C = (x(p), y(p))^T$ with parameter p given by

$$ds = (x_p^2 + y_p^2)^{1/2} dp,$$

to

$$ds_\phi = (x_p^2 + y_p^2)^{1/2} \phi dp.$$

Then we want to compute the corresponding gradient flow for shortening length relative to the new metric ds_ϕ.

Accordingly set

$$L_\phi(t) := \int_0^1 ||\frac{\partial C}{\partial p}|| \phi dp.$$

Let

$$\vec{\mathcal{T}} := \frac{\partial C}{\partial p} / ||\frac{\partial C}{\partial p}|| \ ,$$

denote the unit tangent. Then taking the first variation of the modified length function L_ϕ, and using integration by parts (see [60]), we can show that the direction in which the L_ϕ perimeter is shrinking as fast as possible is given by

$$\frac{\partial C}{\partial t} = (\phi\kappa - (\nabla\phi \cdot \vec{\mathcal{N}}))\vec{\mathcal{N}}. \tag{20}$$

This is precisely the gradient flow corresponding to the miminization of the length functional L_ϕ. The level set version of this is

$$\frac{\partial \Psi}{\partial t} = \phi ||\nabla\Psi|| \mathrm{div}(\frac{\nabla\Psi}{||\nabla\Psi||}) + \nabla\phi \cdot \nabla\Psi. \tag{21}$$

One expects that this evolution should attract the contour very quickly to the feature which lies at the bottom of the potential well described by the gradient flow (21). As in [30, 73], we may also add a constant inflation term, and so derive a model given by

$$\frac{\partial \Psi}{\partial t} = \phi \|\nabla \Psi\| (\operatorname{div}(\frac{\nabla \Psi}{\|\nabla \Psi\|}) + \nu) + \nabla \phi \cdot \nabla \Psi. \tag{22}$$

Notice that for ϕ as in (19), $\nabla \phi$ will look like a doublet near an edge. Of course, one may choose other candidates for ϕ in order to pick out other features.

We now have very fast implementations of these snake algorithms based on level set methods [79, 92]. Clearly, the ability of our snakes to change topology, and quickly capture the desired features will make them an indispensable tool for our visual tracking algorithms.

We are also studying an affine invariant snake model for tracking. (The evolution itself works using a level set model of $\kappa^{1/3}\vec{\mathcal{N}}$ as discussed in Section 4.1.)

5 Concluding Remarks

We have just outlined some of the key findings that we derived in our research under AFOSR Contract AF/F49620-94-1-0461. Much of the work is still continuing. We will briefly describe some of these projects here.

First of all in control, we are extending our work in robust control from linear time-invariant systems to the time-varying case. Further, we are considering a game-theoretic global approach to nonlinear robust control in contrast to the power-series methodology considered above.

In computer vision, we are developing very general segmentation algorithms for both 3D and 4D segmentation. These snake-based techniques will also be very useful in image tracking. We are also exploring putting in probabilistic information in our models, that is combining Bayesian statistics with curve and surface evolution. We are also considering new ideas for shape representation which can be useful for a number of applications including registration in biomedical imaging.

The final goal is a well-developed theory of using vision in a feedback loop, which we regard as one of our major research challenges. This goal still faces a number of daunting technical problems before it can be realized.

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1. Steven Haker (Ph. D.)
2. Anthony Yezzi (Ph. D.)

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Final Report to AFOSR

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1. Research in Signal Processing Partially Supported by Grant AF/F49620-94-1-0461:

Research in the area of signal processing focused on two main topics: watermarking/data embedding for audio, image and video, and analysis and content-based retrieval of visual data. Additional work was done in the areas of low power communications schemes for mobile multimedia, MIDI transcriptions of audio signals and time scale modifications of audio signals.

1.A Main Research Topics:

In this subsection, we will provide an introduction to watermarking/data embedding for audio, image and video, and analysis and content-based retrieval of visual data and summarize our main accomplishments in these areas. Detailed descriptions of the results that we have obtained in these two areas can be found in several journal and conference papers (see Section 5 below) as well as in the theses of J. Nam, B. Zhu and M. Swanson. Additional results will be reported in J. Nam's Ph.D. thesis which is due to be completed in Spring 1999.

1.A.1 Data Embedding and Watermarking

Digital representation has become the preferred format for exchanging, manipulating, storing and playing back audio, image and video signals. Digital media has a high perceptual quality and is easily reproduced, transmitted, stored and edited. These advantages have opened up many new possibilities. In particular, it is possible to embed data (information) within audio, image and video files. The information is hidden in the sense that it is perceptually and statistically undetectable (c.f. Fig. 1). With many schemes, the hidden information can still be recovered if the host signal is compressed, edited or converted from digital to analog format and back.

Data embedding is also referred to as *watermarking*, *data hiding* and *fingerprinting* in the literature. It has many applications. Foremost is passive and active *copyright protection.* Many of the inherent advantages of digital signals increase problems associated with copyright enforcement. For this reason, creators and distributors of digital data are hesitant to provide access to their intellectual property. Copyright information can be hidden in an audio, image or video file by watermarking the file, i.e., making small *imperceptible* modifications to its samples. Unlike encryption, watermarking does not restrict access to digital media. Further, a watermark stays with the media after decryption. It is intended to provide a solid proof of ownership.

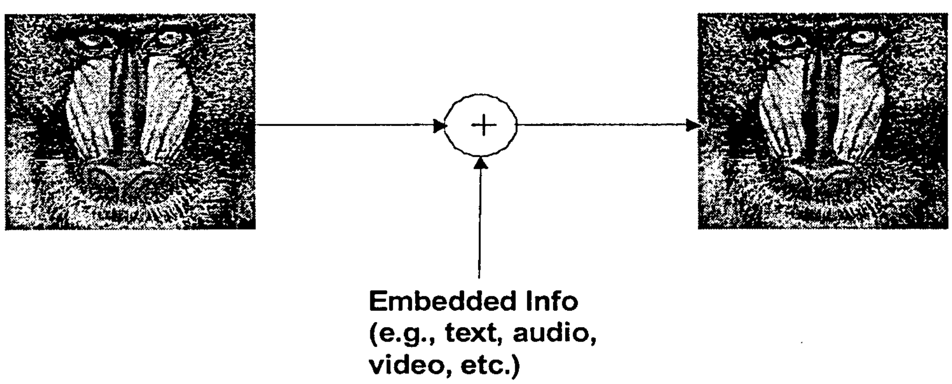


Fig. 1: Block diagram of data embedding procedure

Data embedding also provides a mechanism for inserting additional information in a given signal. This information can be used for:

- *Signal description:* by recording important reference, control and descriptive information about the signal, e.g., an identifier code, capture and reproduction information (recording, camera, scanner or printer parameters), description of the signal content, etc.,

- *Passive rights management and protection:*

  - tracking the use or license of a particular clip, e.g., for pay-per-use applications, including billing for commercials and video and audio broadcast, and internet electronic commerce of digital media,

  - auditing audio or visual object creation dates, manipulation and modification history within a given signal, signal creators and editors, without the overhead associated with creating a separate header or history file,

- *Data privacy and active rights management and protection:* by linking viewing or playing of content to an individual media player or group of players,

- *E-commerce:* by linking the audio, image or video signal to a sales site where users can buy the streamed audio or video signal that they are hearing or viewing,

- *Mass Customization:*

  - Customized advertisements embedded in streamed audio or video,

  - multicasting,

  - personalized multimedia delivery including providing multiple access levels to a given signal,

- *Fraud and tamper-detection* in audio, image or video,

- *Fast download of web pages* with rich multimedia content.

A most interesting example of the last application is personalized video delivery. Personalized video delivery allows users to watch a movie, *broadcast to all viewers over a single channel,* in a particular rating or in a given language of their choice. In this case, data embedding is used to embed extra scenes and multilingual tracks in the given version of the movie that is broadcast. Each user then extracts the hidden information that is needed to reconstruct the movie in the rating and language that he selected. In a sense, data embedding then provides some of the capability of DVD in a broadcast environment with no extra bandwidth or storage requirements.

Data embedding and watermarking research builds on ideas and concepts developed in cryptography, communications theory, algorithm design and signal processing. The data embedding problem is inherently more difficult than any of the problems that have traditionally been addressed in these fields. All data embedding algorithms combine and extend in a sense many of the solutions developed in these areas.

An effective data embedding scheme must at the minimum be able to:

- insert data in the digital signal *without deteriorating its perceptual quality,*

- retrieve the data *without reference to the original host signal.* (This is not a requirement of watermarking schemes which may have access to the original.)

In many applications, the data embedding scheme must also:

- provide *a large data embedding capacity,* i.e., be able to hide the largest number of bits in a given signal. This is particularly important for personalized video delivery or fast download of multimedia rich web pages.

- be *robust,* i.e., be able to retrieve the data even when the host signal has undergone modifications, such as compression, editing or translation between formats, including A/D and D/A conversions (e.g., printing, faxing, copying to analog cassette or VCR tape).

- be *secure, i.e., statistically undetectable*: An unauthorized user should not be able to recover the hidden data by statistically analyzing several media examples with hidden information. This should be true even if he knows the exact data embedding algorithm used, as long as one input to the algorithm (the "key") is not known. Further, an unauthorized user should not be able to establish that data has actually been hidden in a given audio, image or video file.

The security of the data embedding algorithm, like that of most cryptographic procedures, depends on the security of the key. The Serial Copy Management System developed by the digital audio tape (DAT) industry is an example of a poor data embedding and copy protection scheme. The location of the copy protection status information on the tape is fixed and known. As a result, hardware and software are widely available to remove copyright protection from a DAT.

Watermarking algorithms that protect copyrights have another additional stringent requirement:

- they must provide *unambiguous proof of ownership.*

Although this requirement is intuitively obvious, almost all vendors and academic research groups have not recognized it as such. Multiple users can insert digital watermarks in a given digital signal. Unless the watermarking scheme can infer the order in which the watermarks have been added, a deadlock occurs and it becomes impossible to establish who produced or owns the signal. Unlike other data embedding applications, watermarking for copyright protection can make use of the original digital signal for watermark detection. The rightful owner will typically store a copy of the original and could make it available along with a key to a third party that attempts to establish ownership of a signal. Watermarking schemes that require the original data set for watermark detection can also suffer from deadlocks if the watermark is not properly designed. In such schemes, a party other than the owner may counterfeit a watermark by "subtracting off" a second watermark from the publicly available data and claim the result to be his or her original.

Accomplishments:

Our research group has pioneered several data embedding techniques with a number of unique features:

- *truly imperceptible* data embedding in an audio, image or video host signal,

- *highest data embedding capacity*, including the only demonstrated video-in-video application,

- *highly robust hidden data recovery*, even when the host signal had been edited, compressed or undergone translation between formats or A/D and D/A conversions (printing, faxing, copying to analog tape or VCR),

- *true data privacy*

- *secure embedded data,*

- *deadlock free*, i.e., our watermarking techniques provide unambiguous proof of ownership,

- *true video data embedding and watermarking,* *Imperceptibility and high capacity*

The first two features of our data embedding and watermarking techniques stem from a unique data insertion technique that exploits the characteristics of the human visual and auditory system.

Data insertion is possible because a human ultimately consumes the digital media. The human hearing and visual systems are imperfect detectors. Audio and visual signals must have a minimum intensity or contrast level before a human can detect them. These minimum levels depend on the spatial, temporal and frequency characteristics of the human auditory and visual systems. Further, the human hearing and visual systems are characterized by an important phenomenon called masking. Masking refers to the fact that a given audio or visual signal may become imperceptible in the presence of another signal called the masker. Most signal coding techniques exploit the characteristics of the human auditory and visual systems directly or indirectly. Likewise, all data embedding techniques exploit the characteristics of the human auditory and visual systems implicitly or explicitly. In fact, data embedding would not be possible without the limitations of the human visual and auditory systems. For example, it is not possible to modify a binary stream that represents programs or numbers that will be interpreted by a computer. The modification would directly and adversely affect the output of the computer.

Almost all of the data embedding and watermarking schemes available on the market modify the host signal *without explicitly computing the maximum amount of imperceptible modification* that can be introduced within each signal sample or signal transform domain coefficient. Since the modification must be imperceptible, portions of the video, image or audio where modifications are most easily detectable, e.g., smooth regions in an image, limit the magnitude of the modification. As a result, the data extraction performance of these schemes is generally more susceptible to signal perturbations, e.g., compression, editing and noise addition.

In contrast, our data embedding and watermarking techniques *explicitly compute masking information* as a function of space and time. By using this explicit masking information, our data embedding techniques guarantee imperceptibility. Furthermore, they can evaluate the information bearing capacity of any given signal and determine *how to embed* the maximum possible amount of information in that signal.

Typically, blind tests are used to assess the perceptual transparency of data embedding procedures. In such tests, subjects are randomly presented signals with and without embedded data and asked to determine which signal has a perceptually higher quality. A probability of selecting the signal with no embedded data that is roughly equal to 50 percent is indicative of perceptual transparency. Table 1 illustrates the perceptual transparency of our image data embedding technique.

Image	Probability that original is preferred
Lena	53.33%
F16	49%
Houses	49%
Mandrill	49.67%
Peppers	48%

Table 1: Examples of blind test results conducted for our image data embedding technique.

Table 2 provides information about the current capabilities of our data embedding procedures. The amount of data that can be embedded in a given signal decreases with increased robustness requirements. For example, the amount of data that can be embedded and successfully extracted from a signal that may undergo digital to analog conversion (e.g., recording on an analog audio or video tape, faxing or printing) is less than that which can be embedded in a signal that is guaranteed to remain unedited (e.g., a signal stored in read-only form in a data base). Fig. 2 shows an original 512x512 gray scale image and the same image with 4 Kbytes of data embedded in it.

Host Signal	Byte rate or byte density
Audio	2 – 250 bytes/sec in mono CD quality audio signal
Image	8 – 256 bytes in 8 bits gray scale 128x128 image
Video	900 – 9216 bytes/sec in 320x240 8 bit gray scale 24 frames/sec video

Table 2: Data embedding rates for our data embedding approaches. The lower byte rates correspond to the highly robust embedding mode that can survive severe compression and editing including digital to analog conversion. The higher byte rates are less robust but will tolerate modest compression and editing.

(a)

(b)

Fig. 2: (a) Original image, (b) Image with 1 Kbytes of data embedded.

Robustness

Our data embedding and watermarking techniques achieve robustness by *properly shaping* the data prior to insertion. Shaping is based on *explicit masking information.* It ensures that, after data embedding, the change in each sample of the host signal has the largest possible magnitude while remaining imperceptible. Furthermore, the shaping is designed to *maximize the invariance* of the embedded data to the modifications that can occur when the host signal is edited, compressed, converted from a format to another, printed, scanned, faxed or recorded on analog media. Since detection performance is proportional to the energy of the embedded signal and the robustness of the detector to changes in the embedded signal, our data embedding and watermarking techniques have the highest data extraction performance with excellent perceptual quality.

Tables 3-4 provide examples of the robustness of our data embedding procedures. We note also that we can recover up to 1 Kbytes of embedded data from a 512x512 gray scale image that is compressed at 75% JPEG quality.

Bit rate	Bit recovery
192 Kb/s	100%
128 Kb/s	100%
96 Kb/s	100%

Table 3. Robustness of the audio data embedding procedure at different MPEG coding rates.

Image	Bit recovery
Lena	100%
F16	100%
# of embedded bits	128 in 128x128 gray scale image

Table 4. Illustration of the robustness of the image data embedding procedure to printing and scanning.

Data Privacy

Our data embedding solution offers robust data privacy. The host audio, image or video signal is scrambled using secure cryptographic procedures and the de-scrambling information is securely embedded in the host signal itself. Unlike encryption, this data privacy solution is robust to transmission errors and compression. Furthermore, the data remains private as it is converted from one format to another.

Embedded data security

The security of our data embedding and watermarking techniques results from using random insertion and modification patterns that cannot be broken or guessed in any realistic time. Note that the classical maximal length pseudo noise sequences that many schemes use are insecure. These sequences are generated by linear feedback shift registers. The feedback pattern (i.e., the keys) can easily be guessed given a small number of output bits.

Unambiguous proof of ownership

Our watermarking techniques provide unambiguous proof of ownership by using a *dual watermarking scheme and properly designed watermarking sequences*. The watermarks depend strongly on the digital signal that they are intended to protect. In the dual watermarking scheme, a *pair* of watermarks is embedded into the signal. One watermark is detected with the help of the original data set. The second watermark is detected without reference to the original data set. That watermark is intended to mark the signal that a pirate may claim as his or her original. Either of these schemes alone could provide unambiguous proof of ownership.

True video data embedding and watermarking

Unlike almost all other approaches available on the market which treat video as a sequence of image stills, our video data embedding and watermarking approach takes into account the temporal dimension of a video sequence. As a result, this scheme can hide more information in a given video and is much less susceptible to attacks and detection.

1.A.2 Content Based Retrieval

Digital audio, image and video signals are playing an increasingly important role in the new multimedia world. This has led to the creation of large repositories of audio, image and video information. The proliferation of such repositories has produced a major challenge: how does one efficiently access the auditory and visual information that is stored in these databases? Today, the largest cost factor associated with the creation of multimedia applications is undoubtedly the cost of retrieving and editing the relevant audio, image or video information that resides in such repositories.

Currently, most audio, image and video management systems rely on textual description of their content or keywords. This textual data is referred to as *metadata.* The metadata is organized in a standard database. Searching can then be done using standard Boolean textual database queries, exact or probabilistic matches of the query text. Retrieval can be enhanced by using a thesaurus and taxonomies. *Taxonomies* consist of hierarchical of subject classes that organize the data at various levels, e.g., semantic (politics, fashion, etc.), visual (planes, people, etc.).

A text-only based approach to the organization of audio, image or video databases has several drawbacks. First, many auditory and visual characteristics of the data cannot be adequately described in words, e.g., a particular pitch, color or shape. More importantly, such an approach necessarily relies on human intervention. Human input is expensive. Further, the descriptions that human produce are highly subjective. As a result, queries may produce inaccurate and incomplete results or may fail entirely.

To deal with the subjective nature of human descriptions, strong standardization efforts are under way. These include the MPEG-7 standard, extension of the Dublin Core to images and an initiative of the Library of Congress aimed at standardizing the taxonomy of graphic material.

On the other hand, researchers and users have come to the realization that the full information content of audio, image and video signals can only be exploited if these signals are *managed and manipulated as visual or auditory signals*. The natural approach to managing and retrieving audio or visual data is to deal with the auditory, visual and temporal content of the signal such as pitch, loudness, timbre, rhythm, temporal and spatial patterns, colors, shapes, motion, layout and location information, etc. Queries based on such auditory, visual or temporal information may supplement text-based queries and in many instances are the easiest or only way of formulating a given query. A *content-based data management and retrieval system* is a system that relies primarily on auditory, visual or temporal information to manage and retrieve audio, image and video data. Such systems may be used in conjunction with text-based approaches or may incorporate higher level text-based searching and indexing features.

Content-based retrieval systems differ conceptually from traditional text-based retrieval system in one major respect. Retrievals are based on similarity rather than exact matches. As a result, these systems act more like information filters. False positives may be retrieved and need to be manually discarded.

Several criteria can be used to assess the usefulness of any content-based retrieval system. These criteria include:

- *Visual and auditory interface:* content-based retrieval system use auditory and visual information to formulate a query. Further, they may return many false positives since they look for similarity rather than exact matches. User feedback therefore plays an important role in refining the query. Hence, such systems need advanced visual, auditory and temporal interfaces.

- *Automation:* Retrievals cannot be done by exhaustively looking for given patterns in all signals in the database. Instead, query and retrieval operations examine short form important auditory, visual or temporal features of the signal. The process of extracting these auditory and visual content identifiers is known as indexing. Indexing can be done manually (requiring human intervention), semi-automatically or fully automatically.

- *Adaptability:* An important feature of a content-based-retrieval system is its ability to dynamically adapt its indexing and retrieving function according to the relevance feedback provided by the user.

- *Query nature and abstraction level:* The nature of the queries varies with the domain and application. Queries can involve bibliographic information (e.g., title), subject content (e.g., F-16), structural information (e.g., shot), action content (e.g., taking off), syntax (e.g., open spaces) and subjective component (e.g., description of a mood or impression). Most current commercial content-based query systems are based on color and texture queries. They have limited filtering capability and tend to retrieve many false positives.

- *Categorization:* Content-based retrieval systems should act as sophisticated information filters. As such, they provide machine assisted browsing. Browsing can range from free style to category guided navigation. In many instances, the user does not know what he or she wants to retrieve exactly. Retrieval proceeds by displaying representative examples of the signals in the database. Dynamic reorganization of the information based on relevance feedback can drastically cut search time.

- *Scope:* Another important feature of content-based retrieval system is their ability to catalog and index networked as well as local or server information.

- *Memory requirements (index size):* Content-based retrieval systems create an index that is accessed during the search. An improperly designed index may have a size equal to that of the database. On the other hand, a properly designed index will use a minimum amount of additional disk space while supporting a full range of query features.

- *Speed of retrieval:* In most applications of content-based retrieval systems, the query must be answered while the user is waiting in front of a terminal. Furthermore, in many cases a successful retrieval will involve several iterations. Real time resolution of the queries is therefore critical.

- *Precision and recall:* The value of a content-based retrieval system is directly proportional to the quality of the information filtering function that it provides. That quality can be measured in terms of the false positives that the system returns as well as its ability to retrieve all the relevant signals in the database. The false positive issue is particularly important when dealing with large databases.

Content-based retrieval systems will play a dominant role in many applications including:

- Multimedia document techniqueion

- Electronic consumer transaction systems, e.g., electronic catalogs with multimedia content, on-line sale of audio, image and video content, etc.

- Trademark systems, e.g., logo search

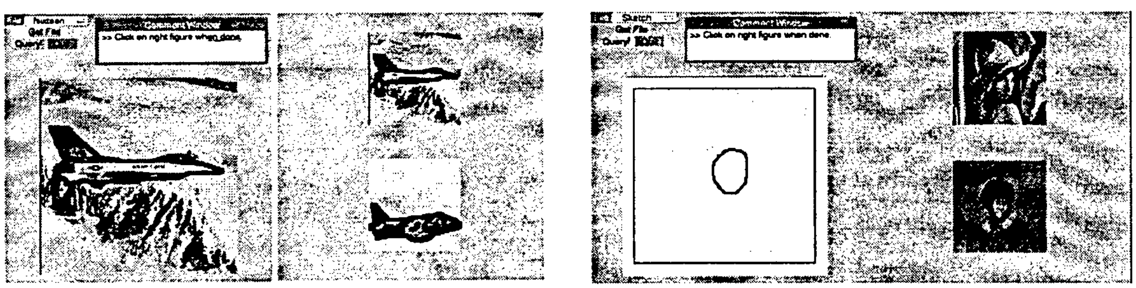
- Law enforcement

- Geographical information systems
- Medical imaging
- Advertisement techniqueion
- Studios
- Broadcast
- Personalized information delivery

Accomplishments

We have developed a content-based retrieval system with several novel key features:

- *Fast retrieval*
- *Low memory requirements*
- *Support for visual query by example, sketch, shape or color*
- *Highly accurate*
- *User friendly visual interface*
- *Fast browsing of networked information*
- *Accurate video analysis tools*



query retrieval query retrieval

(a) (b)

Fig. 3 Screen captures illustrating our content-based image retrieval system and its query type support: a) Query by example, b) query by sketching.

Fast retrieval and low memory requirements

Our content-based image and video retrieval software uses a unique index organization and compression approach that minimizes index size as well as query response time. In particular, the index is optimized for a progressive resolution of the query. Queries are decomposed in a hierarchical manner. At each detail level, the query is resolved using binary string matching procedures: no complex measures are computed.

Visual queries

Our content-based image and video retrieval software supports visual object based query by example, shape or sketch. To formulate a query, a user simply draws a box around an object of interest in the image displayed on the screen. Alternatively, the user can sketch an object. The system then retrieves other images with similarly looking objects.

We are currently extending the system to support color based queries and Boolean combinations of queries.

High accuracy

Several factors account for the high retrieval performance of our content-based image and video retrieval software. First, the software supports object based example specification. This ability to specify more than just the color or texture of the object of interest dramatically reduces false positives. Second, the software uses a smart B-spline based representation of the object contour. This representation provides a large degree of invariance to point-of-view. Therefore, the software can extract images that contain objects viewed from a different angle than the object in the query. Third, the software allows the user to combine multiple queries. Combinations of queries can tighten the specification of the desired object of interest.

Browsing:

Our content-based image retrieval software features a unique object based progressive rendering of images. At the lowest resolution level, objects in an image are represented by generic members of their class. For example, a generic plane may serve as a substitute for a Boeing 747. This unique feature allows the user to browse images on remote servers rapidly while getting a good understanding of the actual composition of the images.

Furthermore, the software automatically organizes images or videos based on content. This enables it to provide dynamic category-based browsing, where the definition of a given category and membership in that category are dynamically refined in response to user relevance feedback.

Accurate video analysis tools

Our video content-based retrieval software uses a unique video segmentation algorithm. The segmentation algorithm breaks the video into shots, scenes and stories. It produces key frames based on a statistical analysis of the video shots and indexes these key frames as well as transition information between key frames. The algorithm also classifies the genre of each shot, e.g., violence, romance, etc., for accurate indexing and retrieval.

1.B Other Areas of Research

We have made several advances in three related areas: low power mobile multimedia communications, MIDI transcription of music and time-scale modifications of audio signals. The results that we have obtained in these areas are described in several journal and conference papers (see Section 5 below) as well as in the theses of N. Sieger and those of K. Hamdy and T.-S. Lan. These last two theses will be completed in Spring 1999.

1.B.1 Low Power Mobile Multimedia Communications

We were the first group to formulate and solve the problem of minimizing the total energy consumed by a mobile multimedia terminal. Our approach consisted in formulating an optimization problem that involves the energy consumed by the coding, error correction and modulation operations involved in such systems subject to a quality constraint. We solved the problem both for static image transmission as well as video transmission. For video transmission, we focused on mode switching in the new H.263 low bit rate video coding format.

1.B.2 MIDI Transcription of Music

We have developed a suite of algorithms for sound segmentation and pitch detection of individual notes. Our pitch extraction algorithms rely on fitting the observed data with entries from a dictionary made of harmonic spectra from samples of music sounds. Our experiments indicate the approach can reliably deal with monophonic sounds and some polyphonic sounds.

1.B.3 Time-Scale Modifications of Audio Signals

We have developed a new approach to time scale modifications of audio signals based on the detection of hyper-peridocities in the signal and the decomposition of basic signal units into harmonic compoenents, attacks and residuals. Our approach uses a different phylosophy than traditional audio time scaling algorithms. It provides a marked improvement in the perceptual quality of the time-scaled audio pieces.

2. Personnel Partially Supported by Grant AF/F49620-94-1-0461:

a. Senior

1. Prof. A. H. Tewfik

b. Research Assistants

1. Mitchell Swanson
2. Bin Zhu
3. Khalid Hamdy
4. Jeho Nam
5. Keesook Han
6. Tse Hua Lan
7. Nicholas Sieger

3. Thesis Completed with Partial Support from Grant AF/F49620-94-1-0461

A. M.Sc. Students:

1. Jeho Nam, Thesis on "Combined Audio and Visual Streams Analysis for Video Sequence Segmentation," December 1996.
2. Nicolas Sieger, Report on "AudioCoding for MIDI", October 1997.

B. Ph.D. Students:

1. Mitchell Swanson, Thesis on "Issues in Multimedia Databases: Coding for Content-Based Image Retrieval and Digital Copyright Protection", March 1997.

2. Bin Zhu, Thesis on "Coding and Data Hiding for Multimedia", July 1997.

4. Honors and Awards of Prof. A. H. Tewfik in the Period 1994-1998

1. *Distinguished Lecturer of the IEEE, Signal Processing Society, 1997.*

2. *Fellow IEEE, 1996.*

3. *Invited Principal Lecturer at the 1995 IEEE EMBS Summer School, Siena, Italy, July 1995.*

4. *Invited Tutorial Instructor at the 1994 IEEE Time-Frequency and Time-Scale Symp., Philadelphia, PA, Oct. 1994.*

5. *Plenary Speaker at the 1994 IEEE Conf. on Acoust. Speech and Signal Proc., Adelaide, Australia, April 1994.*

5. Publications Partially Supported by Grant AF/F49620-94-1-0461

Book Chapters:

1. "Issues in multimedia databases: Coding for content-based image retrieval and digital copyright protection," M. D. Swanson and A. H. Tewfik, in *The Mathematics of Information Coding, Extraction and Distribution,* G. Cybenko, D. O'Leary and J. Rissanen, Eds., Springer-Verlag, 1998.

2. "Multiresolution and Object Based Video Watermarking Using Perceptual Models," in Wavelet, Subband And Block Transforms In Communications And Multimedia, Ali N. Akansu and Michael J. Medley, Eds., Kluwer Academic Publishers, 1998.

Journal Publications:

1. "Multiresolution Video Watermarking using Perceptual Models and Scene Segmentation," M. Swanson, B. Zhu, A. H. Tewfik and B. Chau, *IEEE J. on Selected Areas in Comm.,* vol. 16, no. 4, pp. 540-550, May 1998.

2. "Robust Audio Watermarking Using Perceptual Masking," M. Swanson, B. Zhu, A. H. Tewfik and L. Boney, *Signal Processing,* vol. 66, no. 3, pp. 337-355, May 1998.

3. "Multimedia Interaction, Personalization and Protection: Data Embedding and Watermarking Technologies," M. Swanson, M. Kobayashi and A. H. Tewfik, invited paper, *Proc. IEEE,* vol. 86, no. 6, pp. 1064-1087, June 1998.

4. "Fast Progressively Refined Image Retrieval," M. Swanson and A. H. Tewfik, invited paper, *Journal of Electronic Imaging,* 1998.

5. "Audio coding for representation in MIDI," N. Sieger and A. H. Tewfik, to appear in *Journal of VLSI Signal Proc. Systems for Speech, Image and Video Tech.,* invited paper, 1998.

6. "Arithmetic Coding with Dual Symbol Sets and Its Performance Analysis,"Bin Zhu and A. H. Tewfik, accepted for publication, to appear in *IEEE Trans. on Image Proc.,* 1999.

Invited Tutorial Presentations

1. "Watermarking for Audio, Image and Video," *1998 IEEE Int. Conf. on Image Processing,* Chicago, October 1998.

Invited Conference Publications:

1. "Transparent Robust Image Watermarking," M. Swanson, B. Zhu and A. H. Tewfik, invited paper, in *Proc. 1996 IEEE Int. Conf. Image Proc.*, Lausanne, Switzerland, Sept. 1996.

2. "Audio Coding: An Overview," A. H. Tewfik, invited paper, in *Twenty-Sixth Annual IEEE Communication Theory Workshop*, Tucson, Arizona, April 1997.

3. "Audio Watermarking and Data Embedding-Current State of the Art, Challenges and Future Directions," invited paper, in *Multimedia and Security Workshop, ACM Multimedia '98*, Bristol, September 1998.

Other Conference Publications:

1. "Image Coding with Mixed Representations and Visual Masking" B. Zhu, A. H. Tewfik and O. Gerek, in *Proc. of the 1995 IEEE Conf. on Acoust. Speech and Signal Proc.*, Detroit, MI, May 1995.

2. "Image Coding with Wavelet Representations, Edge Information and Visual Masking," B. Zhu, A. H. Tewfik, M. A. Colestock, O. N. Gerek and A. E. Cetin, *1995 IEEE Int. Conf. Image Proc.*, Washington, D.C., Oct. 1995.

3. "Image Coding for Content Based Retrieval," M. D. Swanson, S. Hosur and A. H. Tewfik, *1996 Visual Comm. and Image Proc. (VCIP '96)*, Orlando, Fl, March 1996.

4. "Coding for Content-Based Retrieval", M. Swanson and A. H. Tewfik, in *Proc. of the 1996 IEEE Conf. on Acoust. Speech and Signal Proc.*, Atlanta, GA, May 1996.

5. "Digital watermarks for audio signals," L. Boney, A. H. Tewfik and K. Hamdy, in *Proc. IEEE Multimedia Conf.*, Hiroshima, Japan, June 1996.

6. "Digital watermarks for audio signals," L. Boney, A. H. Tewfik and K. Hamdy, in *Proc. of the VII European Signal Proc. Conf. (Eusipco-96).*, Trieste, Italy, Sept. 1996.

7. "Robust Data hiding for images," M. Swanson, B. Zhu and A. H. Tewfik, in *Proc. 1996 IEEE DSP Workshop,* Loen, Norway, Sept. 1996.

8. "Transparent Robust Authentication and Distortion Measurement Technique for Images," B. Zhu, M. Swanson and A. H. Tewfik, in *Proc. 1996 IEEE DSP Workshop,* Loen, Norway, Sept. 1996.

9. "Dual Set Arithmetic Coding and its Application in Image Coding," B. Zhu, E. Yang and A. H. Tewfik, in *Proc. of the VII European Signal Proc. Conf. (Eusipco-96).*, Trieste, Italy, Sept. 1996.

10. "Embedded object dictionaries for image database browsing and searching," M. Swanson and A. H. Tewfik, *1996 IEEE Int. Conf. Image Proc.*, Lausanne, Switzerland, Sept. 1996.

11. "Combined Audio and Visual Streams Analysis for Video Sequence Segmentation," J. Nam and A. H. Tewfik, in *Proc. of the 1997 IEEE Conf. on Acoust. Speech and Signal Proc.*, Munich, Germany, April 1997.

12. "Time-Scale Modification of Audio Signals with Combined Harmonic and Wavelet Representations," K. Hamdy, A. H. Tewfik, T. Cheng and S. Takagi, in *Proc. of the 1997 IEEE Conf. on Acoust. Speech and Signal Proc.*, Munich, Germany, April 1997.

13. "Audio coding for conversion to MIDI," N. J. Sieger and A. H. Tewfik, in *Proc. of the 1997 IEEE Workshop on Multidimensional Signal Processing*, Princeton, NJ, June 1997.

14. "Object Based Transparent Video Watermarking," M. D. Swanson, B. Zhu, B. Chau and A. H. Tewfik, in *Proc. of the 1997 IEEE Workshop on Multidimensional Signal Processing*, Princeton, NJ, June 1997.

15. "Adaptive Low Power Multimedia Communications," Tse-Hua Lan and A. H. Tewfik, in *Proc. of the 1997 IEEE Workshop on Multidimensional Signal Processing*, Princeton, NJ, June 1997.

16. "Affine-Invariant Multiresolution Image Retrieval Using B-Splines," M. Swanson and A. H. Tewfik, *Proc. 1997 IEEE Int. Conf. Image Proc.*, Santa Barbara, CA, Oct. 1997.

17. "Joint Audio-Visual Streams Analysis for Hierarchical Video Shot," J. Nam, E. Cetin and A. H. Tewfik, *Proc. 1997 IEEE Int. Conf. Image Proc.*, Santa Barbara, CA, Oct. 1997.

18. "Data Hiding for Video-in-Video," M. Swanson, B. Zhu and A. H. Tewfik, *Proc. 1997 IEEE Int. Conf. Image Proc.*, Santa Barbara, CA, Oct. 1997.

19. "Multiresolution Video Watermarking Using Perceptual Models and Scene Segmentation," M. D. Swanson, B. Zhu, B. Chau and A. H. Tewfik, *Proc. 1997 IEEE Int. Conf. Image Proc.*, Santa Barbara, CA, Oct. 1997.

20. "Eigen-Image Based Video Segmentation and Indexing," K. Han and A. H. Tewfik, *Proc. 1997 IEEE Int. Conf. Image Proc.*, Santa Barbara, CA, Oct. 1997.

21. "Image Coding by Folding," B. Zhu and A. H. Tewfik, *Proc. 1997 IEEE Int. Conf. Image Proc.*, Santa Barbara, CA, Oct. 1997.

22. "Motion-Based Video Object Indexing Using Multiresolution Analysis," J. Nam and A. H. Tewfik, *Proc. 1998 Electronic Imaging: Science and Tech.*, San Jose, CA, Jan. 1998.

23. "Blind Identification of Single-Input Multiple-Output Pole-Zero Systems," G. Venkatesan, M. Kaveh, A. H. Tewfik and K. Buckley, *Proc. of the 1998 IEEE Conf. on Acoust. Speech and Signal Proc.*, Seattle, WA, May 1998.

24. "Progressive Resolution Motion Indexing of Video Object," J. Nam and A. H. Tewfik, *Proc. of the 1998 IEEE Conf. on Acoust. Speech and Signal Proc.*, Seattle, WA, May 1998.

25. "Audio Visual Content based Violent Scene Characterization," J. Nam, M. Alghoniemy and A. H. Tewfik, *Proc. 1998 IEEE Int. Conf. Image Proc.*, Chicago, IL, Oct. 1998.

26. "Fast Polynomial Regression Transform For Video Database," K. J. Han and A. H. Tewfik, *Proc. 1998 IEEE Int. Conf. Image Proc.*, Chicago, IL, Oct. 1998.

27. "Power Optimized Mode Selection For H.263 Video Coding And Wireless Communications," T. Lan and A. H. Tewfik, *Proc. 1998 IEEE Int. Conf. Image Proc.*, Chicago, IL, Oct. 1998.

28. "Low Complexity Dynamic Region and Translational Motion Estimation for Video Indexing," K. J. Han and A. H. Tewfik, *1998 IEEE Workshop on Multimedia Signal Processing*, Redondo Beach, CA, Dec. 1998.

29. "Unified Framework for Source-Channel-Modulation Coding in Low Power Multimedia Wireless communications," T. Lan and A. H. Tewfik, *1998 IEEE Workshop on Multimedia Signal Processing*, Redondo Beach, CA, Dec. 1998.

6. Interactions

Distinguished IEEE Lecturer Presentations

1. Purdue Univ., Dept. of Electrical Engineering Colloquium, "Multimedia Signal Processing," Nov. 1997.

2. Rochester NY IEEE Signal Processing Chapter, "Multimedia Signal Processing," Nov. 1997.

3. General Electric Corporate Research Laboratory, "Multimedia Signal Processing," Nov. 1997.

4. Washington State University, Dept. of Electrical Engineering Colloquium, "Multimedia Signal Processing," March 1998.

5. NJIT, Dept. of Electrical Engineering Colloquium, "Multimedia Signal Processing," April 1998.

6. University of Minnesota and IEEE Signal Processing Chapter, Twin Cities, "E-commerce, Multimedia and Signal Processing," April 1998.

Other Presentations

1. University of Minnesota, Physics Colloquium, "Wavelets: Theory and Applications," Feb. 1994.

2. ARPA, Washington, D.C., "Robust Multiresolution Integrated Target Sensing And Recognition," July 1994.

3. NSA, Washington, D.C., "Wavelets: Theory and Applications," Jan. 1995.

4. NRaD, San Diego, CA, "Adaptive Waveform Selection for High Resolution Range-Doppler Radar Imaging," Feb. 1995.

5. Texas Instruments, Dallas, TX, "Signal Processing and Multimedia," Jan. 1996.

6. IBM, Tokyo, Japan, "Watermarking Digital Audio and Imagery," June 1996.

7. Tokyo Univ, Dept. of Math., "Wavelets: Potentials and Limitations," June 1996

8. Bilkent Univ., Ankara, Turkey, "Signal Processing and Multimedia," July 1996.

9. NEC, Princeton, NJ, "Digital Watermarks for Audio and Images," Aug. 1996.

10. Northern Illinois University, Dept. of Electrical Engineering Colloquium, "Multimedia: The new Signal Processing Frontier," Oct. 1996.

11. Drexel Univ., Dept. of Electrical Engineering Colloquium, "New Vistas in Signal Processing: The Multimedia Challenge," Nov. 1996.

12. Optical Society of America, Minneapolis Chapter, "Wavelets: Theory and Applications," May 1998.

7. Patents

The following patents were filed:

Filed	Seriel No.	Title	Inventors
8/27/97	918,122	Method and Apparatus for Embedding Data, Including Watermarks, in Human Perceptible Images	Ahmed H. Tewfik Mitchell D. Swanson Bin Zhu
8/27/97	918,125	Method and Apparatus for Video Watermarking	Ahmed H. Tewfik Mitchell D. Swanson Bin Zhu
8/27/97	918, 126	Digital Watermarking to Resolve Claims of Multiple Ownership	Ahmed H. Tewfik Mitchell D. Swanson Bin Zhu
8/27/97	918,891	Method and Apparatus for Embedding Data, Including Human Perceptible Sounds	Ahmed H. Tewfik Mitchell D. Swanson Bin Zhu Laurence M. Boney
8/27/97	921,931	Method and Apparatus for Scene-based Video Watermarking	Ahmed H. Tewfik Mitchell D. Swanson Bin Zhu